7567

Vol 1 of 2

Develop Documentation/Prepare Remedial
Action Concept Plan for Building 24
Contamination Plume at Picatinny Arsenal
Final Report
Contract Number DAAA15-87-D-0220
Task Order 5

submitted to
Peer Consultants, Inc.
1160 Rockville Pike, Suite 202
Rockville, Maryland, 20852
and
U.S. Army Toxic and Hazardous Material Agency
Aberdeen Proving Ground, Maryland, 21010-5401

submitted by
Engineering Technologies Associates, Inc.
3458 Ellicott Center Drive
Ellicott City, Maryland, 21045
(301) 461-9920

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Engineering Technologies Associates, Inc.

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Executive Summary

The Picatinny Arsenal is located in Morris County, New Jersey, approximately four miles northeast of Dover. The installation, officially known as the U.S. Army Armament Research Development and Engineering Center, performs research on munitions and weapons. Recent investigations have found concentrations of trichloroethylene (TCE) and other volatile organic solvents in ground water. The metal plating shop in building 24 has been identified as a possible source of contamination. TCE and other solvents were used in degreasing operations at this metal shop.

Three dimensional models of ground water flow and solute transport were developed and applied to the TCE plume in the shallow aquifers around building 24. These models were used to design remedial action pumping plans to prevent contamination from reaching Green Pond Brook and to clean up the contaminated ground water. Ground water will be pumped from collector wells and piped to a treatment plant, probably an air stripper, where TCE and other volatile organic contaminants will be removed.

The U.S. Geological Survey MODFLOW model was used to simulate the ground water flow at the site. The ground water flow system at the site was represented as a three layer model. The first layer was the water table aquifer in the permeable glacial sediments near the land surface. The second layer was the confined glacial aquifer. The third layer was the fractured limestone and dolomite underlying the glacial sediments. The model was calibrated to the existing observation well data.

A new program was written to translate the output of the MODFLOW model to a format suitable for input to the three dimensional, random-walk solute transport model (RAND3D). This program (PREMOD3D) computes three dimensional velocity vectors and sink (wells, gaining streams) locations for input to RAND3D.

Six different pumping schemes for remedial action were then simulated using the three dimensional solute transport model, RAND3D. This model uses the random walk algorithm to simulate contaminate movement in ground water. Several significant improvements were made to the model for this study.

All of the pumping scenarios tested will form a flow barrier in the water table aquifer and thus prevent TCE and other ground water pollutants from reaching Green Pond Brook. They are also all relatively effective in forming a flow barrier in the confined glacial aquifer, where small amounts of TCE have been detected. Significant amounts of TCE have not been detected in the bedrock aquifer. The

proposed remedial action pumping plan will prevent TCE and other contaminants from reaching surface water.

All of the scenarios tested will remove TCE from the water table aquifer effectively. TCE concentrations in the collector wells should be less than 5 ppb after less than 10 years of continuous pumping. After six years of pumping, between 91 and 95 percent of the TCE will have been removed from the aquifers by any of the collection well plans simulated.

The recommended collector well layout is three wells spaced at approximately 480 feet that span the plume of contamination from Building 24. These wells may be placed in the rough of the golf course. The locations are recommended in the body of the report.

The treatment system for the contaminated pumpage should be designed conservatively. Pumpage from the three wells should be between 100 and 150 gallons per minute. The exact pumping rates should be determined after the wells are drilled and tested. The peak composite concentration of TCE in the pumpage from three collector wells would be approximately 750 ppb. The length of the clean up is uncertain. Depending on the significance of TCE adsorption in the aquifer and the initial concentrations of TCE in the area, the wells and treatment system may have to be operated for between six and twenty years. This estimate assumes there are not any significant amounts of TCE still entering the aquifers.

I. Introduction

Engineering Technologies Associates, Inc. is pleased to submit this report on the development of a three dimensional, solute transport model of the Building 24 ground water contamination plume at the Picatinny Arsenal in New Jersey and the conceptual design of a remedial action plan for the collection of contaminated ground water. The objectives of this study were to develop a three dimensional ground water solute transport model to simulate the plume,and to design an effective pumping scheme that would prevent contamination from reaching Green Pond Brook and effectively collect ground water at the Building 24 site.

The Picatinny Arsenal is located in Morris County, New Jersey, and is the home of U.S. Army Armament Research and Engineering Center, performing research on munitions and weapons. Figure I-1 shows the location of the Picatinny Arsenal. Recent investigations by the Arsenal, the U.S. Geological Survey, and the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) have found concentrations of trichloroethylene (TCE) and other volatile organic solvents in the ground water. The source of the contamination has been identified as the past activities in Building 24, a metal degreasing operation. This study focused on TCE since TCE is the ground water contaminant with the highest concentrations and widest distribution in ground water.

The objectives of the study were met by performing the following tasks:

- calibration of the U.S. Geological Survey MODFLOW finite difference ground water model to the aquifers at the Building 24 site;
- development of a computer program to interface the MODFLOW model output with the three dimensional, solute transport model, RAND3D, which uses the random walk algorithm to simulate contaminant movement in ground water;
- application of the RAND3D model to the movement of TCE;
- testing of six different pumping schemes for remedial action;
- sensitivity analysis to test the credibility of the model predictions; and
- writing of model documentation.

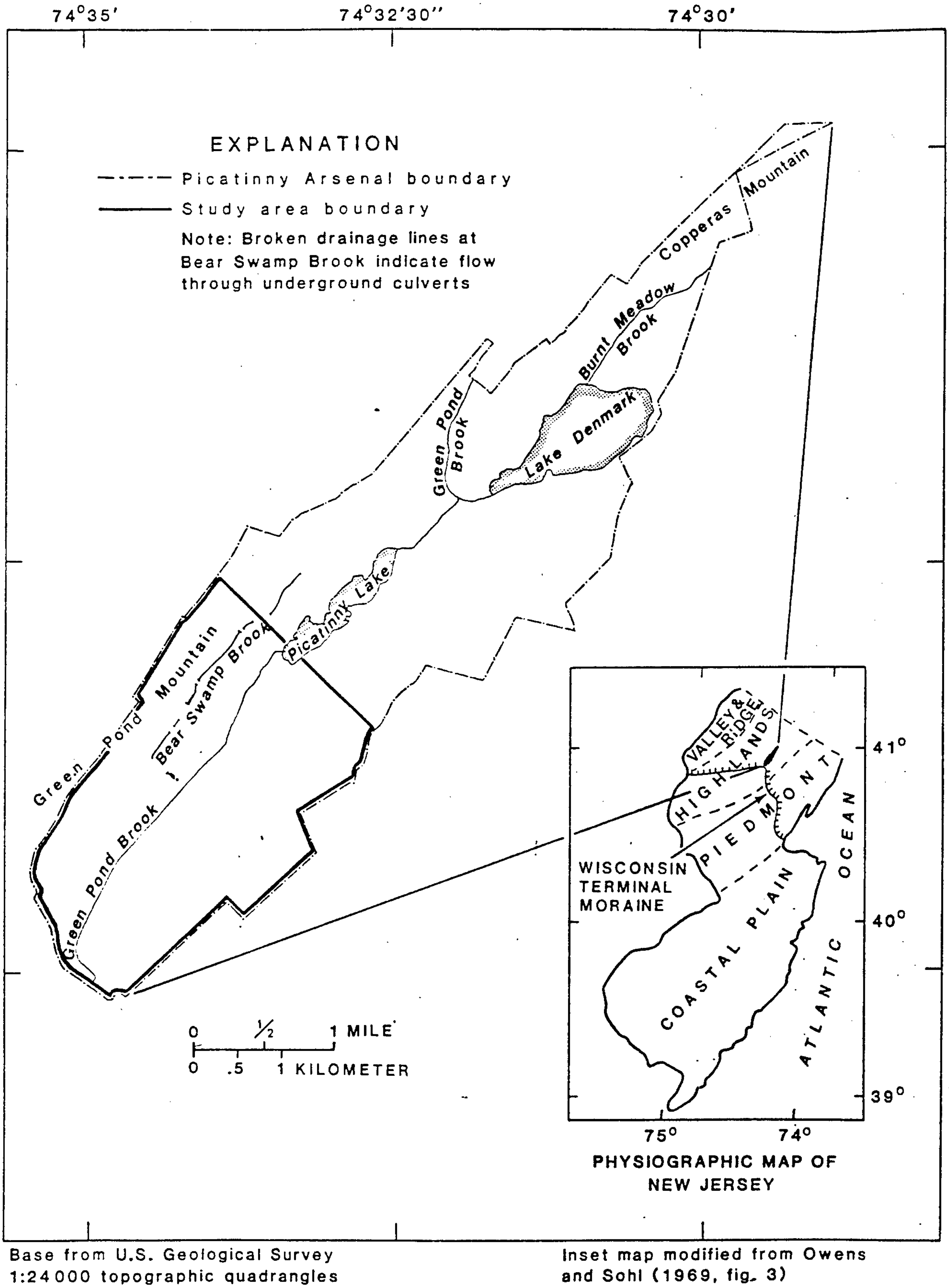

Figure I-1 -Picatinny Arsenal, study area, and New Jersey physiography.

Source:
U.S. Geological Survey

II. Model Theory and Testing

A. MODFLOW - A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model

1. Description

The U.S. Geological Survey three-dimensional finite difference model, MODFLOW, (McDonald and Harbaugh, 1984) was used as the flow model for simulating flow around the Building 24 TCE plume at the Picatinny Arsenal. This model was calibrated at steady state and then used to simulate collection wells to be used as part of a remedial action at the site. The McDonald-Harbaugh model is the latest finite difference ground water flow model developed by the U.S. Geological Survey. It is widely used and well documented. It is a true three dimensional model except for the assumption that the vertical component of hydraulic conductivity is aligned with gravity. It has the capability of simulating a heterogeneous aquifer with evapotranspiration, variable well pumpage, drains, rivers, variable recharge, and different boundary conditions under either artesian or water table conditions. It uses the strongly implicit method to solve the finite difference equations.

2. Modifications - well routine

One modification was made to the MODFLOW model for this project. Routines were added to the model to calculate the drawdown at a well. The original model calculates the head at the middle of a node. This head is not the actual head in a well, however. The head losses caused by ground water flowing to a small diameter withdrawal point are not accounted for. It is typically necessary to predict drawdown in the well as well as drawdown in the aquifer. For this reason, several new routines were written for the MODFLOW model. These routines allow the user to calculate drawdowns in the wells. These drawdowns include the effects of flow convergence and well efficiency. It is also possible to create a file of time versus drawdown at a well and have the output show an alphanumeric well name.

Convergence loss is calculated using the semiempirical equation developed by Prickett and Lonnquist (1971). The convergence loss is

$$h = 0.3665(Q/T)\log_{10}(del/4.81r_w)$$

where

h = head loss
Q = pumping rate
T = effective transmissivity

del = geometric mean of node length and width
r_w = well radius

Effective transmissivity is the input transmissivity for the node if the well is in a confined aquifer. If the well is in an unconfined aquifer, effective transmissivity is calculated as the product of the square root of the anisotropy ratio, hydraulic conductivity, and saturated thickness.

Well efficiency is a measure of head losses caused by the gravel pack, and well screen. Well efficiency typically is predicted with an equation of the form:

$$h = A(Q)^a$$

where
A = coefficient
a = exponent, typically between 1 and 3

These equations were added to the MODFLOW model. Input data is in the same format as in the original MODFLOW model; additional input variables appear on each line of the well module input data. The additional input parameters that may be used are

- ALOSS - coefficient in well loss equation (A)
- AEXP - exponent in well loss equation (^{a})
- RWELL - effective radius of well (r_w)
- IWELL - unit number for time versus head output
- WELNAM - 8 character well name that will appear on output

All or none of the above parameters may be used with the modified version of the model. If the above parameters are not entered the model will merely operate as before. Well drawdowns are output by the modified version of MODFLOW whenever heads are printed. If IWELL is greater than zero, time and head in the well are written to unit IWELL, whenever heads are printed. If the well runs dry (only possible in layer type 1 or 3 when the elevation of the bottom of the aquifer is known), the well discharge is set to zero.

Appendix A describes the input format for the modifications to the MODFLOW model and presents listings of the modified and new subroutines.

3. Model Verification

The MODFLOW model is well accepted and has been extensively tested. Changes have been made to the MODFLOW

model for this project, however, and a verification problem was designed to test model operation.

The test problem was the problem of a single well in a leaky artesian aquifer of infinite extent with no storage in the confining layer. The analytical solution to this problem is well known (Hantush and Jacob, 1955). The input to the MODFLOW model was two layers, with 25 columns and 25 rows. The grid spacing was 100 feet in both the row and column directions in the center of the model with progressively larger grid spacings near the edges of the model. The progressively larger grid spacings were used to simulate an aquifer of large extent. The top layer of the model was under water table conditions and had a specific yield of 0.2 and a hydraulic conductivity of 50 ft/day. The bottom layer was under artesian conditions with a storage coefficient of 0.0002 and a transmissivity of 1250 ft^2/day. The well was located in the middle of grid (row 13, column 13) in the bottom layer. The well was pumped for a total time of one day at a rate of 5000 ft^3/day (0.4642 gpm). Twenty time steps with a time step accelerator of 1.1 were used to simulate the one day. Drawdowns were calculated at the well using an effective well radius of 0.5 feet.

Figure II-1 compares the theoretical results to the MODFLOW model results for the drawdown in the well. The comparison of MODFLOW results to theoretical results is excellent. At the end of one day of pumping the error in predicted well drawdown is 0.043 feet or 0.79 percent. At the end of one day of pumping, the error at a radius of 400 feet from the pumping well is 0.017 feet or 1.44 percent. The larger error at the radius of 400 feet is due to boundary effects; an infinite aquifer is difficult to simulate in a finite difference model, so numerical model predictions, for this situation, are always slightly larger than analytical predictions.

B. PREMOD3D

1. Introduction

One of the objectives of this project was to develop a flexible interface between the MODFLOW ground water flow model and the RAND3D solute transport model. MODFLOW is probably the most widely used and well accepted three dimensional, finite difference ground water flow model in the United States. RAND3D is one of the only available models that is able to simulate three dimensional solute transport in a realistic and efficient fashion. The development of the interface program, PREMOD3D, was one of the major successes of the study.

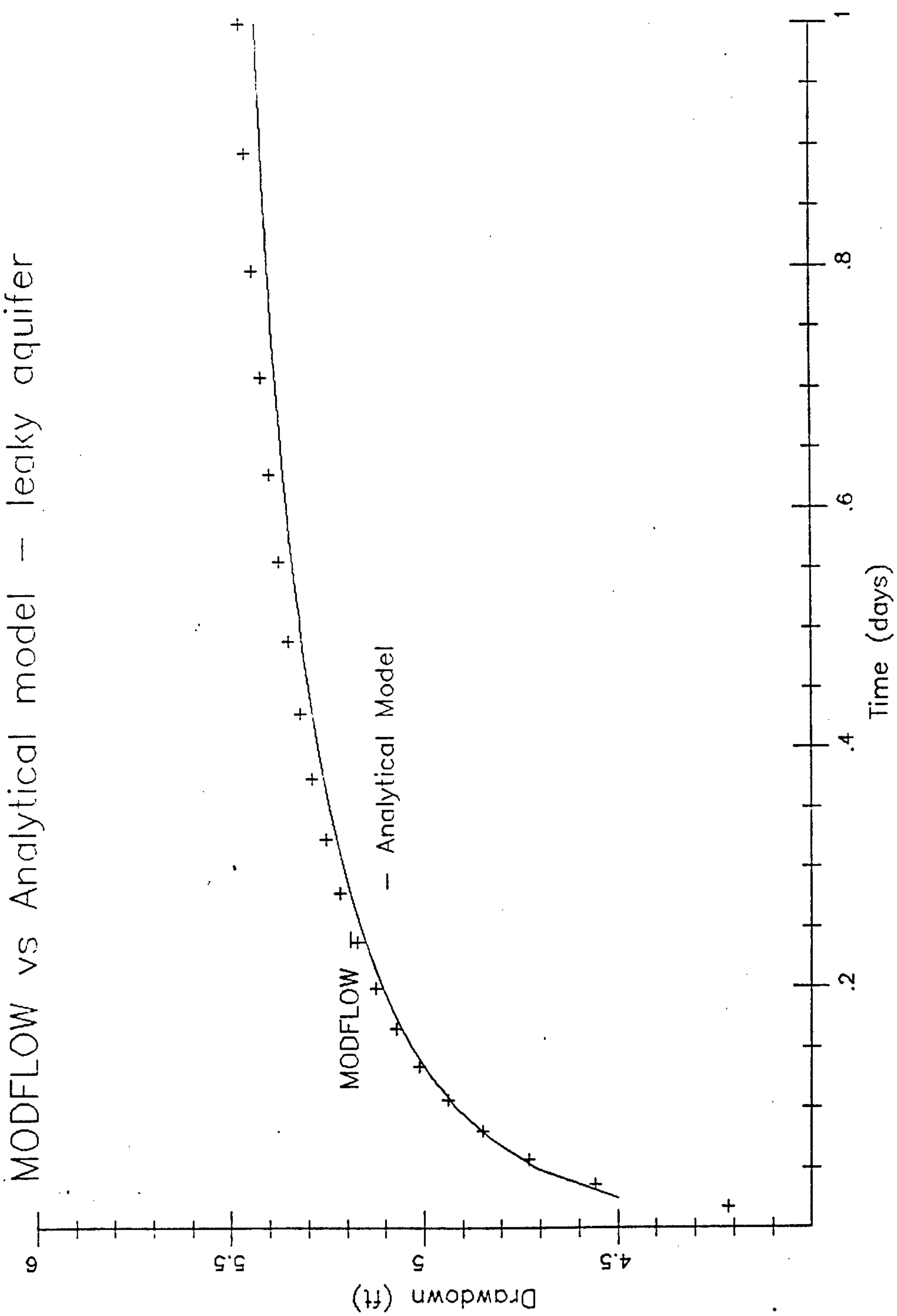
MODFLOW vs Analytical model — leaky aquifer
Drawdown (ft)
6
5.5
5
4.5
Time (days)
.2
.4
.6
.8
1
MODFLOW
— Analytical Model

Figure II-1

2. Description

The function of the PREMOD3D program is to take the output of the MODFLOW model and to prepare the velocity files for the RAND3D model. The program is written in Fortran and compiled using the Microsoft Fortran 3.31 compiler. Many of the subroutines in the program were taken from the MODFLOW model source code. The program calculates the velocity vectors in the x, y, and z directions across each node. The program also calculates the velocity of the water table including the effects of recharge, and evapotranspiration, and the change in elevation since the previous time step. The program calculates the position and flow rate of each sink in the model. Sinks are automatically created at pumping wells, gaining rivers, gaining drains, and gaining general head boundaries. The program creates a velocity file for each time step processed. This velocity file may be input to the RAND3D model. Options in the program permit selection of a subset of the flow model to be used for solute transport calculations, and stress periods to be skipped in the velocity file generation process.

The PREMOD3D program uses the same inputs as the MODFLOW model, plus the head file created by the MODFLOW model. Additional program inputs include a three letter code used in constructing file names for the output files and the rows and columns of the flow model to be used in the creation of the velocity file. The user is prompted for whether or not each stress period is to be processed into a velocity file.

The PREMOD3D program computes the velocity vectors at each node of the model using the hydraulic conductivities input to MODFLOW, the heads generated by MODFLOW and saved in a MODFLOW head file, and grid spacings using Darcy's law. For the top layer of the simulation, the apparent velocity of the water table is calculated as the change in head since the last time step plus the vertical flow effects of recharge, evapotranspiration and river leakage. Sink locations are computed by the PREMOD3D program based on the inputs of wells, rivers, drains, and general head boundaries. There are a set of subroutines that read in MODFLOW data (the same subroutines that are used in the MODFLOW program) and then create sinks using the same logic that was used to calculate the sink terms of the ground water flow differential equation being solved in MODFLOW. The basic procedure is that each well, drain, river, or general head boundary is tested to see if water is leaving the model during the current stress period. If water is leaving, the flow rate is calculated, and the location of the sink and flow rate are written into the output file.

The PREMOD3D program writes the velocity file for use by the RAND3D program. Multiple velocity files may be prepared for transient simulations. PREMOD3D is written in Fortran and has the same limitations as MODFLOW regarding grid sizes. Appendix B contains a more extensive discussion of the PREMOD3D program and user documentation.

C. RAND3D - three dimensional random walk model

1. Description

The RAND3D program is a three dimensional version of the random walk algorithm developed by Thomas Prickett at the Illinois Water Survey as an efficient algorithm for solving ground water solute transport problems (Prickett, Naymik, and Lonnquist, 1981). The model was originally developed for two dimensional solute transport. Thomas A. Prickett and Associates developed a three dimensional version of the model. Further modifications and improvements were made to the model as part of this project.

The random-walk technique is based on the concept that dispersion in porous media is a random process. A particle, representing the mass of a specific chemical constituent contained in a defined volume of water, moves through an aquifer with two types of motion. One motion is with the mean flow (along streamlines determined by finite differences), and the other is random motion, governed by scaled probability curves related to flow length and the longitudinal and transverse dispersion coefficients. Enough particles are included in simulations so that their locations and density, as they move through a flow model, are adequate to describe the distribution of the dissolved constituent of interest. Each particle represents a fixed mass of solute. As more particles, with correspondingly smaller masses, are used in a given simulation, accuracy improves.

The two other commonly used algorithms in ground water solute transport are the method of characteristics, and the direct finite element solution of the differential equation of solute transport. The random-walk algorithm has a number of advantages over these other common solute transport algorithms. The random-walk algorithm is not subject to mass balance errors or numerical dispersion. It is extremely efficient for typical ground water contamination problems where the solute of interest only exists in a small area of the aquifer; the random-walk algorithm only performs calculations where the plume (particles) are, the other algorithms perform computations in all model nodes. It may be easily scaled for any level of resolution by changing the number of particles. The model can operate under immiscible flow conditions (plug flow) without the numerical instabilities common with other models.

One of the major features of the RAND3D model is its interactive operation on an IBM PC or compatible microcomputer. After velocity files are prepared using PREMOD3D or some other suitable procedure, the user may use this program to simulate solute transport and watch the results on the monitor. The program operates from a menu. The user is prompted for all data inputs. A major feature of the model is the ability to display geographic features on the computer screen and superimpose the plume simulation. The user may zoom in on any area of the model to see a more detailed simulation. The geographic features are input by the user in any convenient right-handed (x-y) coordinate system in feet (such as a State Plane coordinate system). These features may then be displayed on the screen as background reference for the plume simulation.

The RAND3D model includes the following features:

- calculation of horizontal advective transport based on a four point interpolation of the input velocity vectors;

- calculation of vertical advective transport based on linear interpolation between the input vertical velocity vectors at the top and bottom of each layer;

- calculation of dispersion using constant dispersivities, longitudinal, transverse, and vertical;

- calculation of first-order decay;

- calculation of linear, reversible adsorption (retardation);

- the ability to originate solute (particles) in the model as sequences of prisms, cylinders, or lines;

- calculation of solute concentrations exiting the model at sinks (wells or gaining streams);

- mapping of solute concentration in user selected areas of the model, either plan viewor cross-section concentration maps may be prepared;

- output of gridded solute concentrations by layer for plotting;

- interactive operation;

- on-screen display of plume (particle) movement in user selected area;

- on-screen display of user input geographic features at user selected scale as background for the plume display;

- saving and viewing of screen slides;

- saving and restart of model parameters at any time;

- transient flow simulations may be simulated by inputting a series of velocity files.

The RAND3D model was designed for an IBM PC or compatible microcomputer with 640K, a numeric coprocessor, a hard drive, and a color monitor with a color graphics adapter. The program is written in Microsoft Quick Basic Version 3.0. Current limits in the program are:

- maximum input grid of 45 columns, 45 rows, and three layers;

- maximum number of particles is 10000;

- maximum number of sinks (wells or gaining streams) is 99;

- maximum number of special feature files is 20.

A full description of the algorithm, the program, and user instructions are in Appendix C.

2. Model Verification

Extensive modifications were made to the RAND3D program for this project. It was necessary to verify the modifications by comparing the output of the RAND3D program with an analytical solution.

There are relatively few three dimensional analytical solutions for solute transport. One of the simplest is the problem of a single instantaneous, point source of solute in a uniform flow field, with dispersion in all three dimensions. The analytical equation describing this problem is

$$C = [M/(8n(\pi^3 t^3 D_x D_y D_z)^{.5}]\exp(-(x-vt)^2/4D_x t - y^2/4D_y t - z^2/4D_z t)$$

(Hunt, 1978)

where
C = concentration
M = initial mass entering aquifer as a slug
x,y,z = cartesian coordinates, slug source is at 0,0,0 and direction of flow is along x axis

v = seepage velocity in x direction
D_x = dispersion in x direction = $\alpha_x v$
D_y = dispersion in y direction = $\alpha_y v$
D_z = dispersion in z direction = $\alpha_z v$
n = porosity
t = time since addition of slug
exp = exponential function (inverse natural log)

This equation was used to calculate the plume resulting from the instantaneous addition of 50 lbs of solute to an aquifer with a uniform seepage velocity of one ft/day. The theoretical aquifer porosity was assumed to be 0.1. Dispersivities were assumed to be 10 feet in the longitudinal direction, 3 feet in the transverse direction, and 1 foot in the vertical. With the seepage velocity of one foot/day, the resulting dispersion coefficients were 10, 3 and 1 ft^2/day. Concentration plumes were calculated at a time of ten days for a ten foot thick horizontal section (layer 2) centered on z=0 and a vertical cross-section centered on y=0.

The RAND3D model was run for the same situation. A 14 column by 11 row by 3 layer grid was designed. Column and row widths were ten feet. Layer two was ten feet thick, layers one and three were twenty feet thick. A uniform velocity field with a Darcy velocity in the x direction of 0.1 ft/day was prepared. There was no retardation or decay. Five thousand particles were placed in the middle of row 6, column 5, layer 2 (model coordinates 50,55,25) as a slug source. Each particle weighed 0.01 lbs. The model was run for 10 days and maps and plots prepared.

Figure II-2 shows the concentrations in layer 2 after ten days from the RAND3D model. Figure II-3 shows the corresponding analytical solution. They match extremely well. There are some differences due to the stochastic nature of the RAND3D algorithm. Some distortion and averaging resulted from the gridding algorithm used to prepare the contour plots. The peak concentration in the analytical solution is 797 mg/l at x=60, y=55. The peak concentrations in RAND3D are 722 mg/l at x=55, y=55 and 770 mg/l at x=65 and y=55.

Figure II-4 shows the concentrations in row 6 of the model from the RAND3D model. Figure II-5 shows the corresponding analytical solution. The extent of the plume matches well. The gridding algorithm smoothed the peak in the middle of the model plume. The peak concentration in the middle of the plume in the analytical solution is 941 mg/l at x=60, z=25. The peak concentration in the middle of the plume in the RAND3D output is 936 mg/l at x=60, z=25. The differences are due to the random-walk nature of the algorithm.

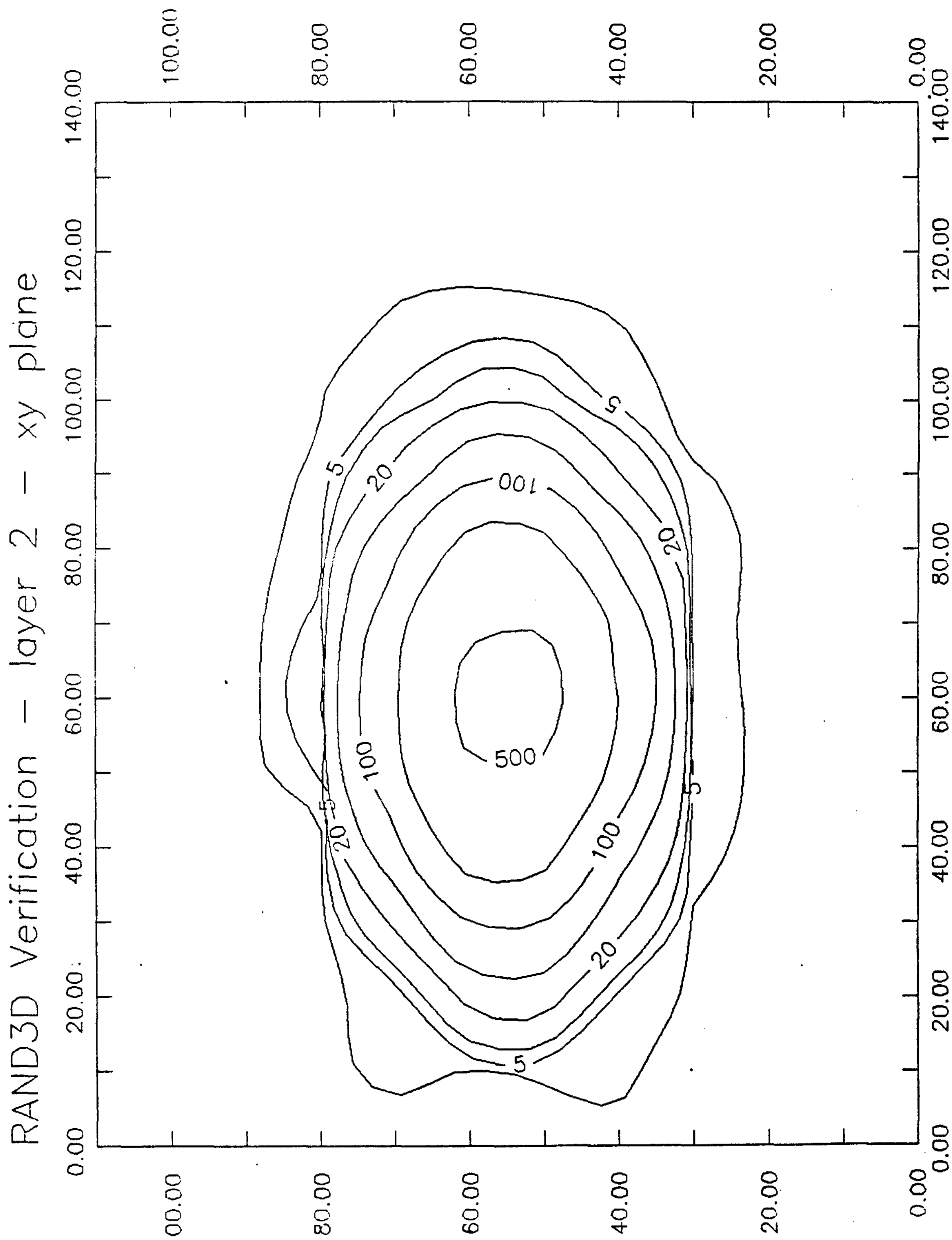
RAND3D Verification - layer 2 - xy plane
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
100.00
80.00
60.00
40.00
20.00
0.00
5
20
100
500

Figure II-2

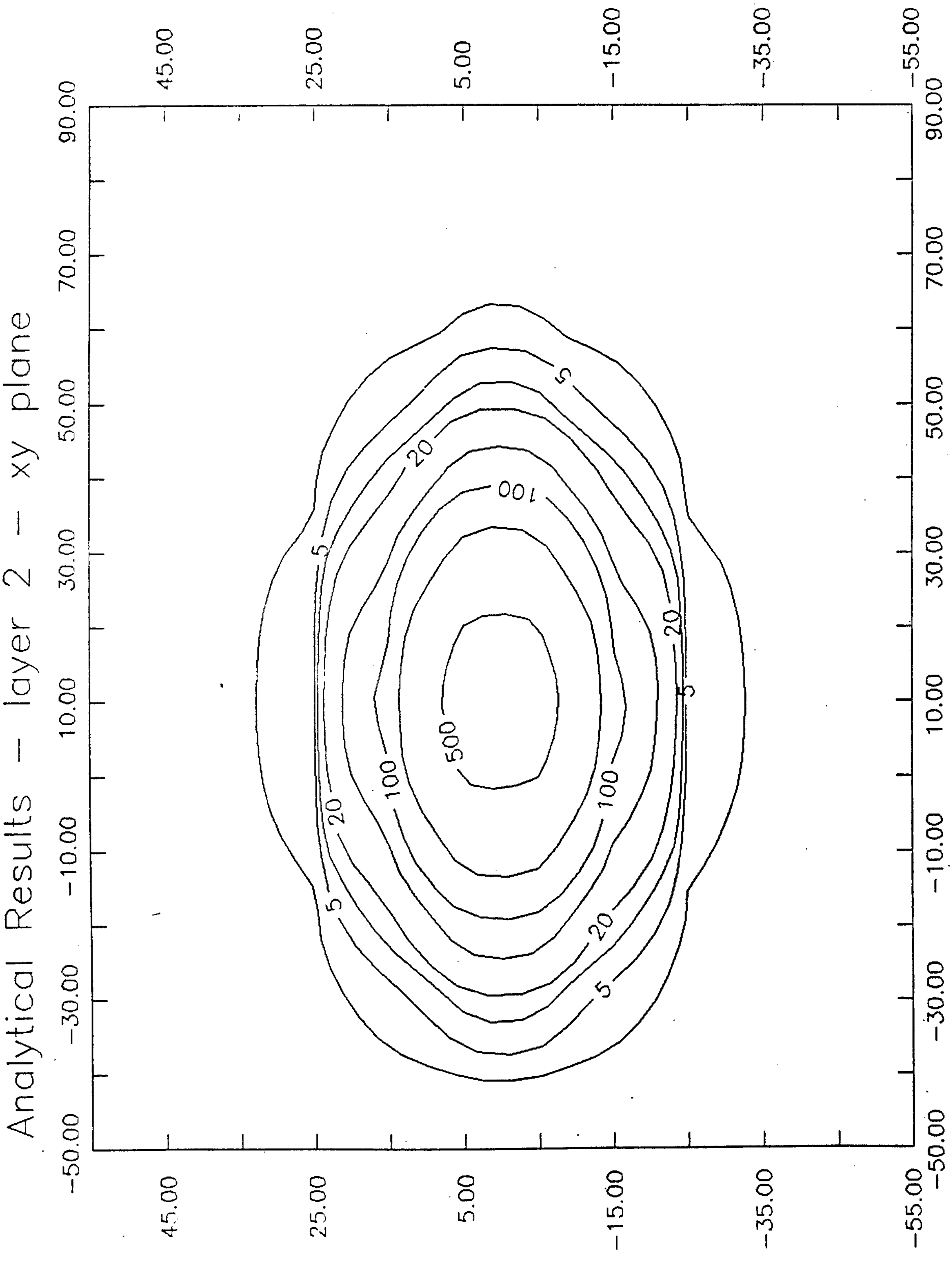
Analytical Results - layer 2 - xy plane
-50.00
-30.00
-10.00
10.00
30.00
50.00
70.00
90.00
45.00
25.00
5.00
-15.00
-35.00
-55.00
5
20
100
500

Figure II-3

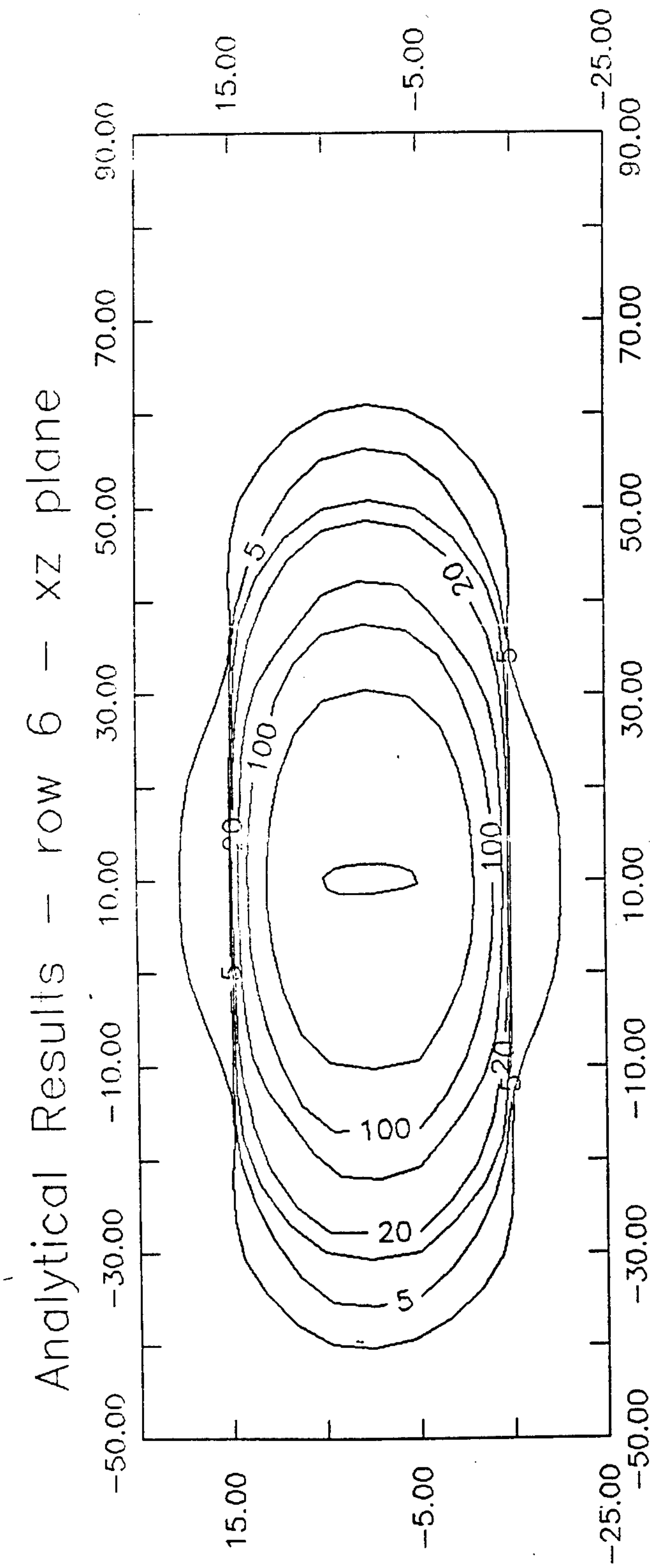
Analytical Results – row 6 – xz plane
-50.00
-30.00
-10.00
10.00
30.00
50.00
70.00
90.00
15.00
-5.00
-25.00
5
20
100

Figure II-4

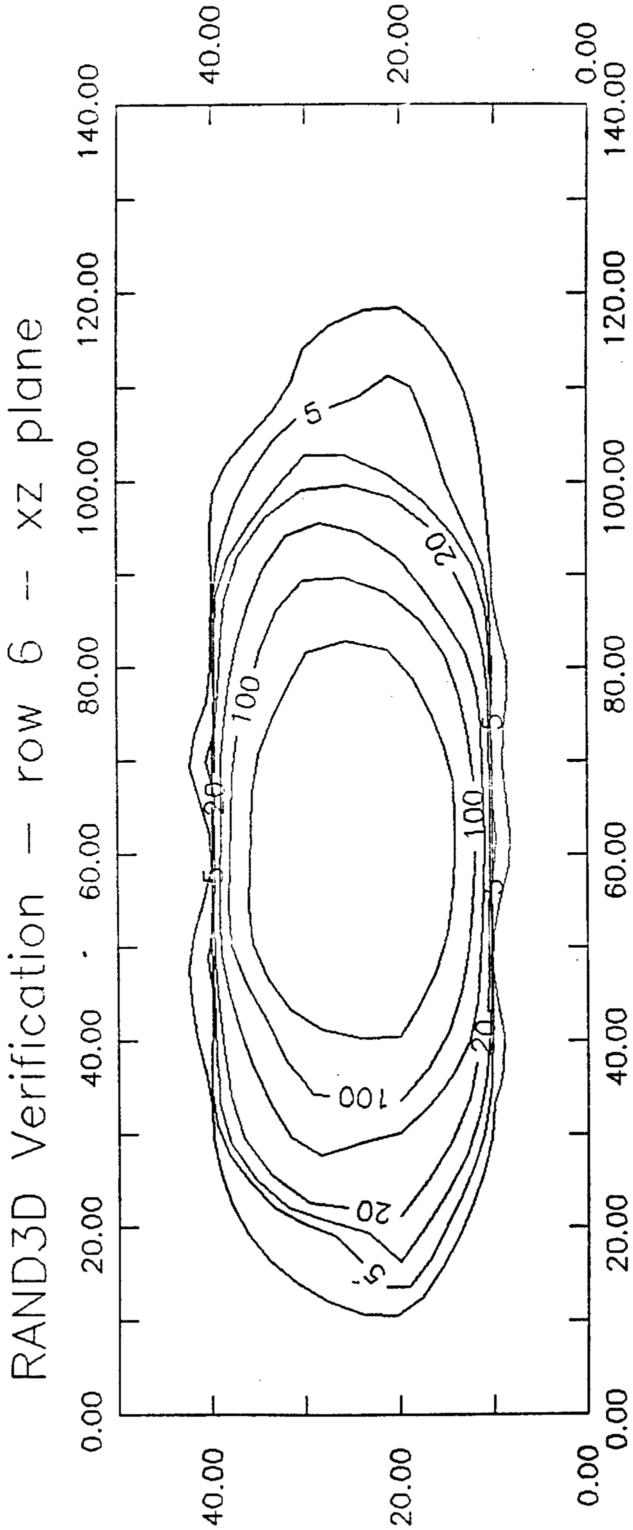
RAND3D Verification – row 6 – xz plane
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
5
20
100

Figure II-5

One common criticism of the random-walk algorithm is that it does not yield exact answers. Model output tends to be somewhat "lumpy", especially at the edges of a plume where the particles are sparse. Model output may always be improved by adding more particles where this is a problem. Real world data are frequently "lumpy" also, however. Application of solute transport models to real world problems typically does not require great precision, since there is typically uncertainty in real world hydrogeologic data. Even with relatively few particles, the random-walk algorithm is quite capable of simulating most ground water contamination problems with adequate resolution.

III. Application to Building 24 Contamination Plume

A. Background

The Picatinny Arsenal is located in Morris County, New Jersey, approximately four miles northeast of Dover. The installation, officially known as the U.S. Army Armament Research Development and Engineering Center, performs research on munitions and weapons. Recent investigations have found concentrations of trichloroethylene (TCE) and other volatile organic solvents in ground water. The metal plating shop in building 24 has been identified as a possible source of contamination. TCE and other solvents were used in degreasing operations at this metal shop.

The basic sources of data for this study were a series of reports prepared by the United States Geological Survey office in Trenton, New Jersey (Sargent et al, 1988; Fusillo et al, 1987; Harte et al, 1986; Sargent et al, 1986; Lacombe et al, 1986; Vowinkel et al, 1985). These reports describe the geology, hydrology, hydrogeology, and water quality of the Picatinny Arsenal. All of the data used in this study was taken from these reports. Some original interpretations were made where necessary to improve the modeling effort, but generally the interpretations of these reports were trusted.

The study area is located in the drainage basin of Green Pond Brook, which is a tributary to the Rockaway River. The Rockaway River flows into the Boonton Reservoir, a water-supply reservoir for Jersey City. Green Pond Brook runs through the middle of the Arsenal.

The Picatinny Arsenal is located in the Green Pond Syncline, a structural region within the New Jersey Highlands physiographic province. The New Jersey Highlands is comprised of a northeast-southwest system of folded and faulted Proterozoic to Devonian rocks that form a sequence of valleys and ridges. The Green Pond syncline is a narrow, northeast-trending, faulted syncline containing a thin section of Paleozoic sediments. Bedrock at the site consists of gneiss, quarzite, dolomite, and conglomerate. The bedrock is overlain by approximately 200 feet of glacial deposits. The glacial deposits are stratified, consisting of sublacustrine sands and gravels, lake-bottom silts, and deltaic sands and gravels (Sargent et al, 1988).

Ground water flow at the site generally follows the topography; ground water flows towards Green Pond Brook and down valley. Vertical gradients are downward except around Green Pond Brook where there is some upward movement of ground water. In the valley, three aquifers have been defined, an unconfined stratified-drift or water-table

aquifer, a confined glacial aquifer, and a bedrock aquifer. The water table aquifer occupies the deltaic sands and gravels at the surface. The confined glacial aquifer comprises the sublacustrine sand and gravel which is separated from the water table aquifer by the lake bottom fine sand and silt. The lake-bottom fine sand and silt acts as a leaky confining bed. Ground water movement in the bedrock aquifer is dependent on the secondary porosity provided by solution channels and fractures. Estimated horizontal seepage velocities are from 0.42 to 1.8 feet/day (Sargent et al, 1988).

Numerous monitoring wells have been installed at the site between 1983 and 1988. In addition to these data, there were production wells in the vicinity. Table III-1 shows the available well data. Figure III-1 shows the site and well locations.

Lithologic logs were available for most of the wells listed in Table III-1 (see Sargent et al, 1988; Harte, 1986; and unpublished driller logs from the 1987 drilling). In addition to lithologic logs, gamma logs were performed on some of the wells drilled in 1986 and 1987, although the gamma logs were depicted at a small scale, preventing any detailed lithologic interpretation. The lithologic logs confirmed the geologic interpretation in Sargent et al, 1988.

> Deglaciation began approximately 18,000 years ago and progressed in stages in the Green Pond Brook Valley. The southern most extent of glaciation is delineated by a terminal morraine at the southwestern boundary of the arsenal. The initial retreat of ice north of the terminal moraine caused the formation of a temporary proglacial lake in the Green Pond Brook Valley. Glacial Lake Picatinny was dammed across the south end by the moraine and the glacier blocked northward drainage. However, drainage for the lake could occur to the southeast through a gap in a bedrock ridge at an elevation of approximately 700 feet. This is approximately the present altitude of the study area. The Lake was filled with a sequence of sediments, starting with sublacustrine sand and gravel, overlain by lake-bottom and deltaic fine sand and silt and capped by deltaic sands and gravels (Sargent et al, 1988).

Table III-1
Picatinny Arsenal Well Data
from Sargent et al, 1988

Local well ID	Date Completed mm/dd/yyd	Altitude of land surface (ft)	Screen setting Top (ft)	Screen setting Bottom (ft)	Screen Diameter (in)	Static Water level (ft)	Date water level measured mm/dd/yy	Geologic Unit
302D	1/ 1/21	697	110	403	8	8	1/ 1/21	bedrock
65-1	12/16/82	699.1	267	287	4	11.5	12/22/82	bedrock
CAF-1	11/12/82	702.7	253	268	4	6.3	12/15/82	bedrock
10-3A	8/ 5/87	701.9	249.5	264.5	4	4	9/29/87	bedrock
H-2	4/18/84	699.2	203	223	4	11.33	11/28/84	bedrock
39-1	8/26/87	692.7	195	205	4	3.04	2/ 1/88	glacial
65-2	12/ 9/82	699.9	201	206	4	11.25	1/12/83	glacial
95-2	9/28/87	695.2	190	200	4	4.52	10/ 6/87	glacial
CAF-4	12/10/82	702.9	168	173	4	11.8	12/17/82	glacial
65-3	12/15/82	700	135	140	4	4.2	1/12/83	glacial
H-3	4/20/84	699.2	115	125	4	9.61	11/28/84	glacial
CAF-3	11/17/82	702.3	123	128	4	13.7	12/ 9/82	glacial
95-1	9/ 9/87	695.2	100	120	4	3.09	9/30/87	glacial
39-2	8/28/87	692.4	90	100	4	3.53	2/ 1/88	glacial
10-4	8/11/87	701.9	85.5	95.5	4	8.55	9/25/87	glacial
112-7	8/ 5/87	695.7	46.1	51.1	2	6.67	8/27/87	glacial
92-3	8/ 3/87	700.2	50.2	55.2	2	9.84	9/ 4/87	glacial
CAF-6	8/ 6/87	702.7	50.9	55.9	2	10.98	9/ 3/87	glacial
112-3	8/ 5/87	698.2	46.1	51.1	2	8.79	9/ 3/87	glacial
41-1	7/22/87	692.6	39.6	44.6	2	2.91	8/20/87	glacial
112-6	7/30/87	695.6	36.1	41.1	2	6.35	8/27/87	glacial
41-8	8/ 4/87	690.5	30.8	35.8	2	2.7	9/ 2/87	glacial
41-4	7/23/87	688.6	28.1	33.1	2	2.16	9/ 2/87	glacial
I-2	7/29/87	693.2	31.9	36.9	2	3.66	8/26/87	glacial
112-4	7/30/87	698.3	37	42	2	8.93	9/ 3/87	glacial
92-4	7/31/87	699.9	38	43	2	9.53	9/ 4/87	glacial
112-9	8/ 6/87	694.3	31	36	2	5.41	8/26/87	glacial
112-1	7/27/87	697.2	32	37	2	7.61	8/24/87	glacial
111-1	7/28/87	702.5	36.1	41.1	2	11.3	8/25/87	glacial
I	12/30/81	693.3	9	29	4	5.5	12/30/81	glacial
CAF-2	11/15/82	702.7	31	36	4	10.9	12/ 8/82	glacial
65-4	12/15/82	699.9	30	33	4	9.35	12/21/82	glacial
41-3	7/21/87	689.5	17.1	22.1	2	3.54	8/21/87	glacial
92-5	7/31/87	699.6	25.9	30.9	2	9.13	9/ 3/87	glacial
41-5	7/23/87	686.8	12.2	17.2	2	2.61	9/ 2/87	glacial
41-9	7/30/87	690.4	15.8	20.8	2	4.39	9/ 2/87	glacial
31-2A	8/ 3/87	702.1	25.9	30.9	2	9.73	8/28/87	glacial
9-D	8/ 4/87	702.2	26	31	2	8.51	9/10/87	glacial
41-2	7/21/87	692.6	15.6	20.6	2	5.69	8/20/87	glacial
130-3	8/ 1/85	701.8	23	28	2	11.2	8/ 2/85	glacial
H-4	4/23/84	699	15	25	4	9.7	11/28/84	glacial
CAF-5	4/25/84	703.2	24	29	4	10.88	2/ 1/88	glacial
112-8	7/29/87	695.6	15.9	20.9	2	6.52	8/26/87	glacial

Table III-1 (continued)
Picatinny Arsenal Well Data
from Sargent et al, 1988

Local well ID	Date Completed mm/dd/yyd	Altitude of land surface (ft)	Screen setting Top (ft)	Screen setting Bottom (ft)	Screen Dia-meter (in)	Static Water level (ft)	Date water level measured mm/dd/yy	Geologic Unit
112-2	7/27/87	696.9	15.9	20.9	2	7.27	8/24/87	glacial
111-2	7/27/87	702.4	20.9	25.9	2	11.19	8/25/87	glacial
112-5	7/30/87	698.2	15.9	20.9	2	8.82	9/ 3/87	glacial
24-1	7/11/85	701.4	18	23	2	7.9	8/ 2/85	glacial
31-1	7/12/85	702.6	19	24	2	10.6	8/ 1/85	glacial
112-10	7/30/87	694.3	10.7	15.7	2	5.53	8/26/87	glacial
9-B	3/ 9/81	702	3	23	4	8.9	9/11/84	glacial
31-3A	7/11/85	702.2	13	23	2	9.9	8/ 2/85	glacial
34-1	7/11/85	703.2	19	24	2	12.6	8/ 2/85	glacial
9-A	3/ 9/81	701.3	2	22	4	8.3	3/19/85	glacial
64-1	8/ 1/85	701.5	17	22	2	9.2	8/ 2/85	glacial
129-OBS	8/26/83	703.4	19	23	2	13.3	3/20/85	glacial
31-5	10/15/86	703	11	21	4	8.43	12/17/87	glacial
31-7	10/10/86	702.2	10	20	4	7.21	12/17/87	glacial
9-E	8/ 4/87	702.2	14.2	19.3	2	8.64	9/10/87	glacial
31-6	10/17/86	702.2	8	18	4	6.86	12/17/87	glacial
34-2	10/23/86	703.3	8	18	4	9.89	12/17/87	glacial
9-C	3/ 9/81	702.1	6	16	4	6	3/ 9/81	glacial
10-3	10/13/86	702	5	15	4	5.64	12/17/87	glacial
129	2/27/48	704	98	120	8	14.5	2/27/48	glacial
130	2/27/48	701.1	102	117	10	11.6	2/27/48	glacial

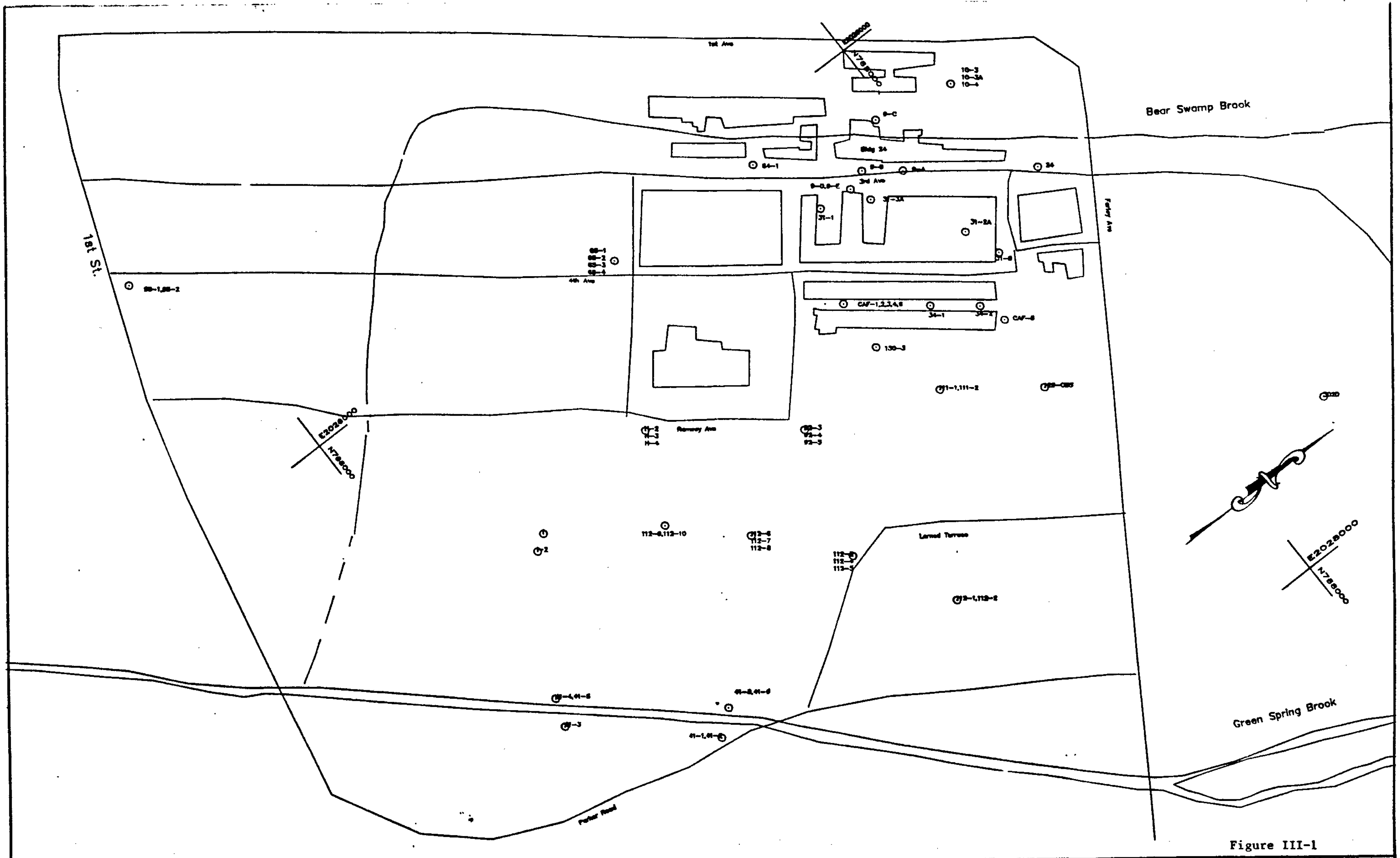

Figure III-1

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DRAWN	PPM 12-89
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WELL LOCATIONS

SCALE 1" = 250'

The study site is in a classical U-shaped glacial valley with steep sides and flat lying unconsolidated glacial sediments.

There were limited data on aquifer characteristics available. Specific capacity tests had been performed on most of the wells listed in Table III-1. Slug tests were performed on the two inch diameter wells installed in 1987. The production wells, 129 and 130, were pump tested in 1965 and again in 1983. No pump test data were available for the bedrock or water table aquifer. Table III-2 shows the available aquifer characteristic data.

The last column in Table III-2 shows the transmissivity derived from the specific capacity using the Hurr method. The Hurr method is essentially an inverse drawdown analysis using the Theis equation for nonsteady flow in an infinite, confined aquifer. A storage coefficient was assumed, 0.1 for the water table aquifer and 0.0001 for the confined aquifer and the following equation applied.

$$uW(u) = \pi r^2 Ss/tQ$$

where

$uW(u)$ = product of parameter and exponential integral
$u = r^2S/Tt$
$W(u)$ = exponential integral, Theis nonsteady well function
r = well radius
S = storage coefficient
s = drawdown during specific capacity test
t = duration of specific capacity test
Q = pumping rate
T = transmissivity

The result of this table is used with a figure prepared by Hurr (Kruseman and De Ridder,1979) to find u. The equation for u is used to derive T, transmissivity. Hydraulic conductivity was derived from transmissivity by dividing by the screened interval. Given the short duration of the specific capacity tests, it was assumed that the screen interval was better than the full water table aquifer thickness (about 50 feet) for calculating hydraulic conductivity. Both arithmetic and geometric mean transmissivities and hydraulic conductivities were computed for the water table aquifer.

Table III-2
Pump Test Data in the study area

Local well identifier	Pumping Water Depth (ft)	Pumping Period (hrs)	Yield (gpm)	Specific Capacity (gpm/ft)	Aquifer	Slug test K (ft/day)	Trans-missivity (ft2/day)	Hydraulic Conductivity (ft/day)
302D	38		490	16.33	bedrock			
65-1	125	3.8	4.5	0.04	bedrock		8.8	0.44
CAF-1	146.8	2.7	3	0.02	bedrock		4.1	0.27
10-3A	28.8		2	0.08	bedrock			
H-2			5		bedrock			
39-1	171		0.5	0.01	confined			
65-2	25.3	0.2	9	0.64	confined?		138.9	27.78
95-2	28.48		2.5	0.1	confined			
CAF-4	156.8	1.7	4	0.03	confined		4.9	0.98
65-3	123	0.1	5.5	0.05	confined?		7.2	1.45
H-3	56.77	0.8	10	0.21	confined?		41.7	4.17
CAF-3	123	0.2	4	0.04	confined?		5.6	1.11
95-1	30		0.5	0.02	confined?			
39-2	70.8	1.5	1.8	0.04	confined?		6.5	0.65
10-4	25		6	0.36	upper			
112-7	28.82	1.8	1	0.05	upper	1	4.2	0.84
92-3	31.78	1	6	0.27	upper	6	36.2	7.25
CAF-6	28.93	0.6	4.5	0.24	upper	4.5	39.7	7.94
112-3	30.05	1.5	5	0.24	upper	6	27.8	5.56
41-1		3	1.6		upper			
112-6	21.88	0.8	15	0.97	upper	12	130.2	26.04
41-8	27.35	2	1	0.04	upper	1	3.5	0.69
41-4	25.07	1	2.5	0.11	upper	0.5	11.9	2.38
I-2	15.5	0.5	4	0.34	upper	5	41.7	8.33
112-4	30.06	1	3	0.14	upper	2	16.7	3.33
92-4	23.05	.0.8	12	0.89	upper	14	115.7	23.15
112-9	11.78	0.6	4.5	0.71	upper	12.5	92.6	18.52
112-1	10.32	2.2	2.2	0.81	upper	15	126.3	25.25
111-1	17.61	1	2.5	0.4	upper	477	69.4	13.89
I	9.5		10	2.5	upper			
CAF-2	31		10	0.5	upper			
65-4	19.12	0.2	12	1.23	upper		111.1	37.04
41-3		2.2	1.4		upper			
92-5	23.33	0.7	8	0.56	upper	10	79.4	15.87
41-5	10.85	0.7	18	2.18	upper	59	297.6	59.52
41-9	15.43	1	14	1.27	upper	14	166.7	33.33
31-2A		1	18		upper			
9-D	12.19	2	5	1.36	upper	24	208.3	41.67
41-2		4	1.1		upper			
130-3	16.8	0.5	12	2.14	upper		333.3	66.67
H-4	11.34	5	10	6.1	upper		1111.1	111.11
CAF-5					upper			
112-8	12.96	0.3	7	1.09	upper	13	126.3	25.25
112-2	7.83	0.5	20	35.71	upper	122	6666.7	1333.33
111-2	14	0.8	16	5.69	upper		868.1	173.61

Table III-2
Pump Test Data in the study area

Local well identifier	Pumping Water Depth (ft)	Pumping Period (hrs)	Yield (gpm)	Specific Capacity (gpm/ft)	Aquifer	Slug test K (ft/day)	Trans-missivity (ft2/day)	Hydraulic Conductivity (ft/day)
112-5	17.97	0.8	15	1.64	upper	20	208.3	41.67
24-1	11.8	1	6	1.54	upper		208.3	41.67
31-1	13.6	1.5	1.5	0.5	upper		61.7	12.35
112-10	12.68	0.8	30	4.2	upper	37	651.0	130.21
9-B		0.5			upper			
31-3A	12.4	0.7	12	4.8	upper		744.0	74.40
34-1	15.4	1	4	1.43	upper		20.8	4.17
9-A	9.2	1	1	1.11	upper		144.9	7.25
64-1	18	0.4	8	0.91	upper		122.5	24.51
129-OBS	16.1	2	1	0.36	upper		52.1	13.02
31-5					upper			
31-7					upper			
9-E	13.5	0.8	6	1.23	upper		173.6	34.04
31-6					upper			
34-2					upper			
9-C			2		upper			
10-3					upper			
		water table aquifer arithmetic mean				40.7	396.11	73.45
		water table aquifer geometric mean				10.5	105.75	19.87

Meaningful averages for the bedrock and confined glacial aquifer were difficult to compute. Some of the wells were completed in strata where it is difficult to determine whether that strata are part of the bedrock aquifer or glacial confined aquifer. There were only two bedrock wells with specific capacity tests and nine wells that may be completed in glacial confined aquifer. The average hydraulic conductivity of the two bedrock tests was 0.35 ft/day. No averages for the confined glacial aquifer wells were computed because better data were available.

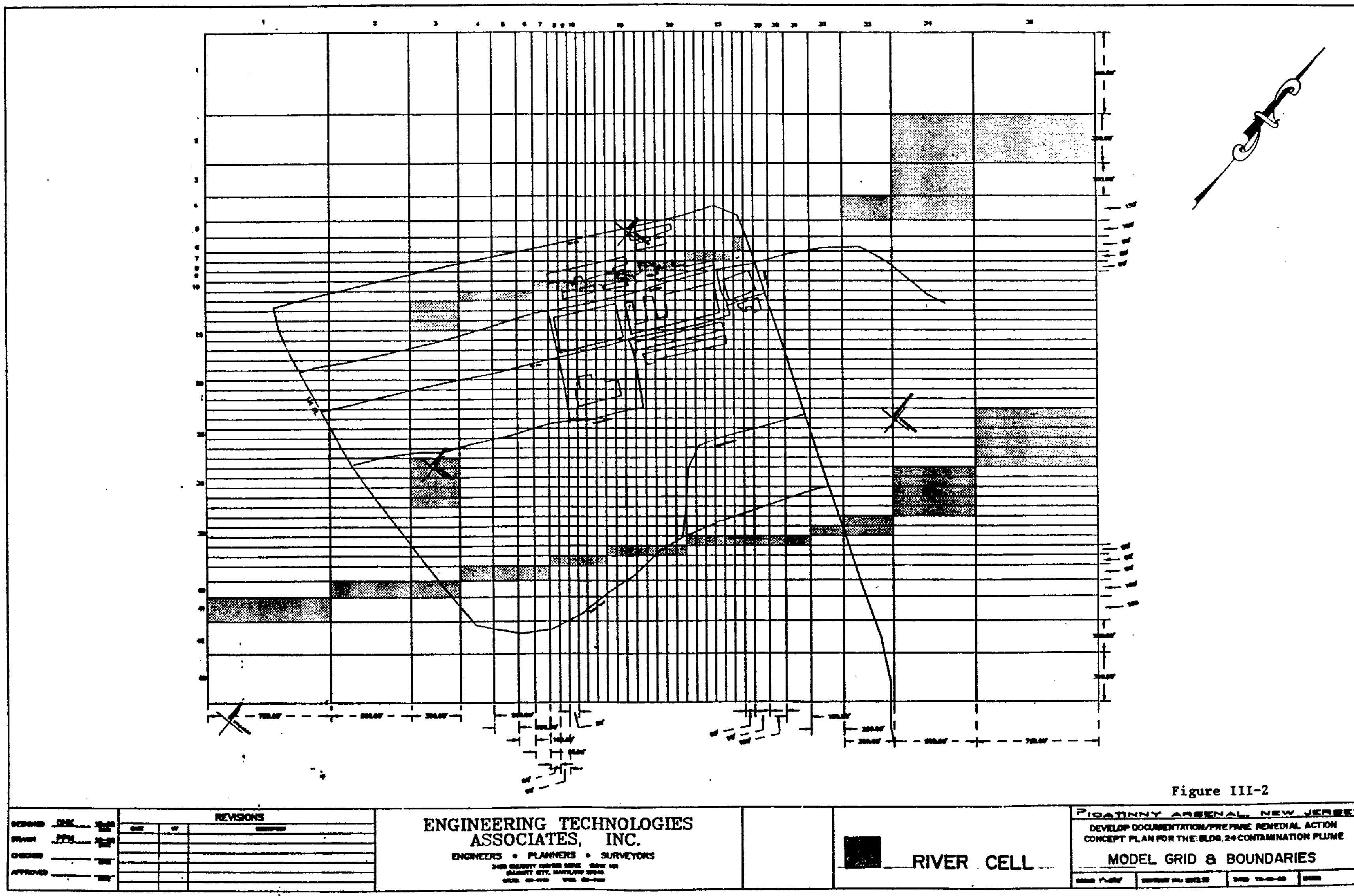
There were also data from three multiwell pump tests in the confined glacial aquifer. The production wells were tested three times in past years. Well 130 was tested in 1965. A transmissivity of 5570 ft^2/day was reported. Well 129 was tested in 1965 and 1983. Transmissivities from these tests were reported as 7424 and 6867 ft^2/day. The storage coefficient from the 1983 test of well 129 was 0.0001 and the vertical hydraulic conductivity through the confining bed was 0.6 ft/day (Sargent et al, 1988).

B. Flow Model Setup and Data Assumptions

1. Grid and boundaries

The flow model was setup as a three layer model with confining beds separating the layers. This model design was based on the interpretation of the ground water system at the site by previous investigations (Sargent et al, 1988). The three aquifers in the model were the water table aquifer at the top of the glacial till, the confined glacial aquifer at the bottom of the till, and the fractured bedrock underlying the till.

The grid was based on the need to simulate a large enough area to permit accurate simulation of well pumping, while using a close equally spaced grid for contamination simulation. The RAND3D model requires an equally spaced grid. The flow model grid was thus designed so that the edges of the model were far enough from the TCE plume area so accurate well simulation could be performed, while having an adequate number of equally spaced grid nodes in the area where TCE movement was simulated. A 35 column by 43 row grid was defined as shown in Figure III-2. The area where the TCE plume presently exists (Sargent et al, 1988) was covered by grid nodes that were 60 feet on a side. Beyond this area, a variable grid spacing was used to permit the boundaries to be at least 2000 feet from the probable locations of collector wells.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MODEL GRID & BOUNDARIES

Figure III-2

The grid was oriented so that the columns were aligned with the direction of flow as revealed by the TCE plume (Sargent et al, 1988).

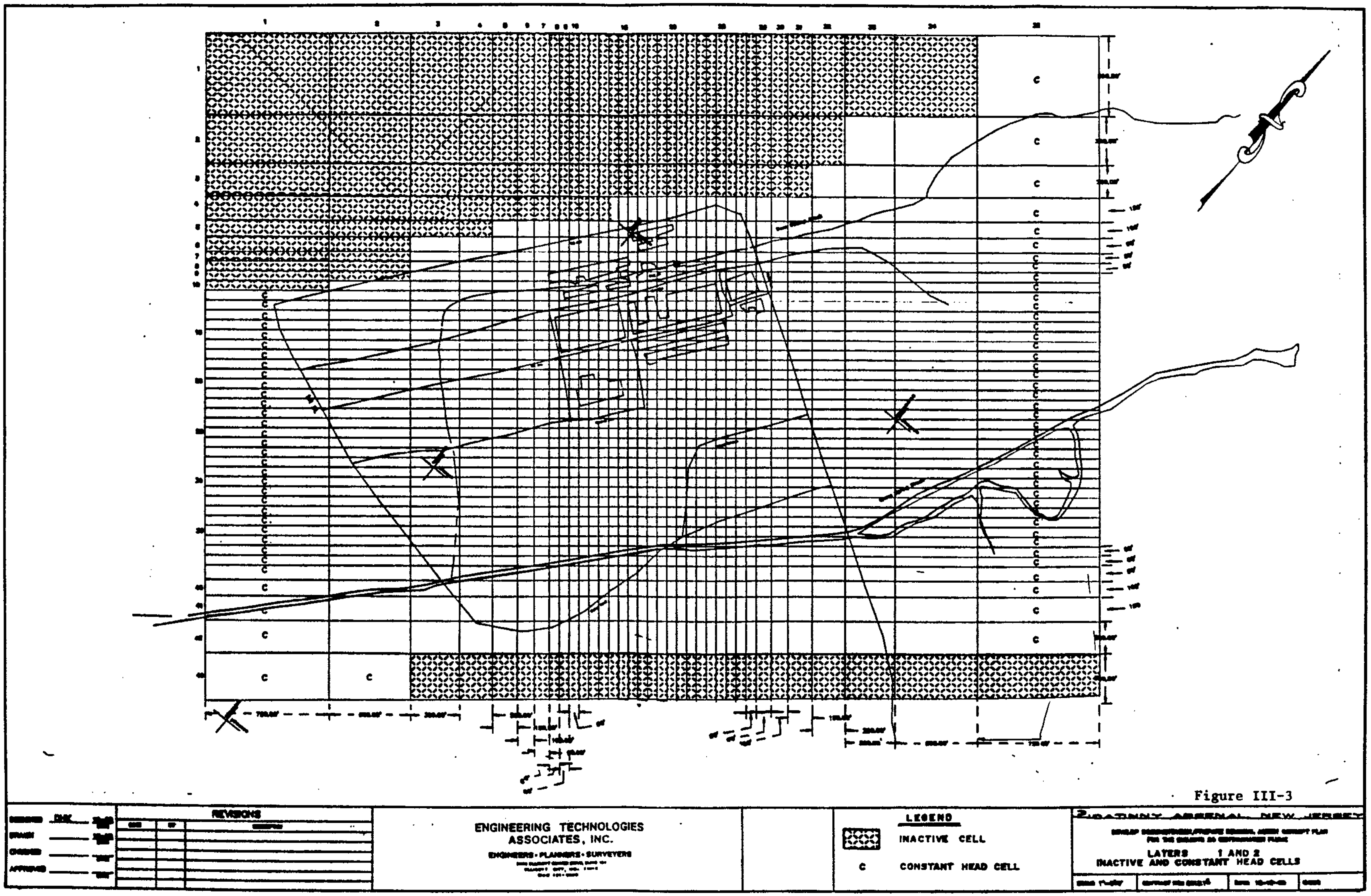
The bedrock aquifer was present throughout the model grid. There was a constant head boundary at the edges of the model bedrock aquifer. The water table and confined glacial aquifers were assumed to not exist on the steeply sloping sides of the valley; thus noflow boundaries were placed on the valley sides. There were constant head boundaries at the upstream and downstream ends of the valley in the modeled water table and confined glacial aquifers. Figure III-3 shows the assumed constant head and noflow boundaries of the water table and confined glacial aquifers.

2. Aquifer delineation

Delineating the top and bottom elevations of the three aquifers to be simulated was difficult. The glacial till did not exhibit well defined lithologic divisions; changes were gradational. Many of the well lithologic logs exhibit gradual changes from sand and gravel (obviously capable of transmitting significant quantities of ground water) to silty clay layers that would act as confining layers. Picking the tops and bottoms of the three layers on each well log also was difficult. Correlating these tops and bottoms across the site was more difficult. Several of the deeper wells drilled in 1987 (10-3A, 39-1, 95-2) did not have finished lithologic logs, only driller logs.

Originally, the intention was to base the model aquifer delineation on Figure 10 from <u>Ground-water Contamination in the Area of Building 24, Picatinny Arsenal, New Jersey</u> (Sargent et al, 1988). Inspection of the data indicated that there might be problems with this approach, so the available lithologic logs were inspected carefully, Ultimately, the model aquifer delineation used did not differ significantly from Figure 10.

Many of the lithological logs were inspected (see Sargent et al, 1988; Harte et al, 1986, and driller's logs). The most common stratigraphic pattern was sand and gravel at the surface ranging in thickness from five to fifteen feet. This material was underlain by sands, which were underlain by alternating layers of silt, sand, and clay. These alternating layers of silt, sand, and clay were assumed to be the confining bed between the water table and confined glacial aquifers and were up to 150 feet thick. There was typically a stratum of sand, gravel, cobbles, and boulders next in the sequence which was assumed to comprise the confined glacial aquifer. Beneath this was weathered bedrock. The bedrock evidently weathers to clay-like material (driller's logs noted clay where weathered bedrock should have been



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LAYERS 1 AND 2
INACTIVE AND CONSTANT HEAD CELLS

Figure III-3

found). The bedrock was the Leithsville Limestone; cavities were noted in this strata on some logs (Harte et al, 1986).

There were many variations of the pattern described above. Of some concern was the thickness/existence of the confining layer between the water table and confined glacial aquifer at different locations. Figure 10 of Ground-water Contamination in the Area of Building 24, Picatinny Arsenal, New Jersey (Sargent et al, 1988) indicated that the confining layer between the water table and confined glacial aquifer was missing in the vicinity of Building 24. Inspection of the driller's log from well 10-3A, which is north of Building 24, indicated a thick sequence of alternating sand, silt, and clay which would act as an effective confining bed.

The confining layer between the bedrock aquifer and the confined glacial aquifer was difficult to define. Most logs show that the sand, gravel, cobbles, and boulders of the confined glacial aquifer directly overlay the weathered bedrock. The water levels indicate that the bedrock and confined glacial aquifers have similar heads, thus one would assume that they are well connected. Inspection of the driller's logs indicates that the weathered bedrock is a clay-like material. The two specific capacity tests in the bedrock (wells 65-1 and CAF-1) indicate a relatively impermeable material, yet some lithologic logs indicate cavities in the limestone and dolomite strata. Cavities would indicate an extremely permeable rock aquifer. The probable explanation for these seemingly contradictory facts is that the fractured bedrock is quite permeable. The bedrock weathers to a clay-like material that plugs fractures near the surface of the bedrock and provides a confining layer between the confined glacial aquifer and bedrock. This interpretation fits the available data and yielded a reasonable model calibration.

The slope of the stratigraphy was also considered. The geologic history of the glacial sediments indicate that the lacustrine strata would be flat-laying. Correlation of lithologic logs show significant changes in aquifer elevation from well to well but no apparent trend. There may be a slight down valley trend that generally matches the topography, but in the area of interest (where the TCE plume has been found) the trend is insignificant. All aquifers were assumed flat-lying.

The water table aquifer was assumed to be approximately 50 feet thick. The bottom of the model water table aquifer was set at 650 feet above mean sea level. The model confined glacial aquifer had a top elevation of 560 feet and a bottom elevation of 520 feet. The model bedrock aquifer was assumed to have a top elevation of 480 feet and a bottom elevation of 430 feet. The bottom of the bedrock aquifer

was arbitrary and had no impact on the model results. Figure III-4 shows a cross-section of the conceptual aquifer model.

3. Aquifer characteristics

Aquifer characteristics, hydraulic conductivity, storage coefficient, and leakance were assigned to model aquifers based on the data previously discussed for initial model simulations. These hydraulic conductivities and leakances were adjusted during the calibration of the model. Storage coefficients were not adjusted since the model was calibrated at steady state.

The water table aquifer was assigned a hydraulic conductivity of 20 ft/day based on the geometric mean value derived from the specific capacity tests. The geometric mean is the best overall measure of central tendency to use with hydraulic conductivity data (Neuman, 1982). Attempts to map hydraulic conductivity in the water table aquifer did not generate any significant pattern. The hydraulic conductivity of 20 ft/day resulted in good calibration results. The specific yield was assumed to be 0.2, a typical value for a sand and gravel water table aquifer.

The leakance of the confining bed between the water table aquifer and the confined glacial aquifer was calculated to be 6.67E-3/day based on the vertical hydraulic conductivity of the confining bed derived from the pump test of well 129, and the assumed thickness of the confining layer, 90 feet.

The hydraulic conductivity of the confined glacial aquifer was assigned based on the 1983 pump test results from well 129. The transmissivity from this test was 6867 ft^2/day. Assuming a confined glacial aquifer thickness of 40 feet, the hydraulic conductivity was 172 ft/day. This value was assigned to all grid nodes and was not changed in the calibration process. The storage coefficient was assumed to be 0.0001 based on the pump test results from well 129.

The initial estimate of leakance in the confining bed between the confined glacial aquifer and the bedrock aquifer was 7.1E-3/day based on an assumed permeability of 1E-4 cm/sec and the assumed thickness of 40 feet. The calibration indicated this value was large and it was ultimately set at 3.5E-3/day.

Picatinny Arsenal Conceptual Aquifer Setup

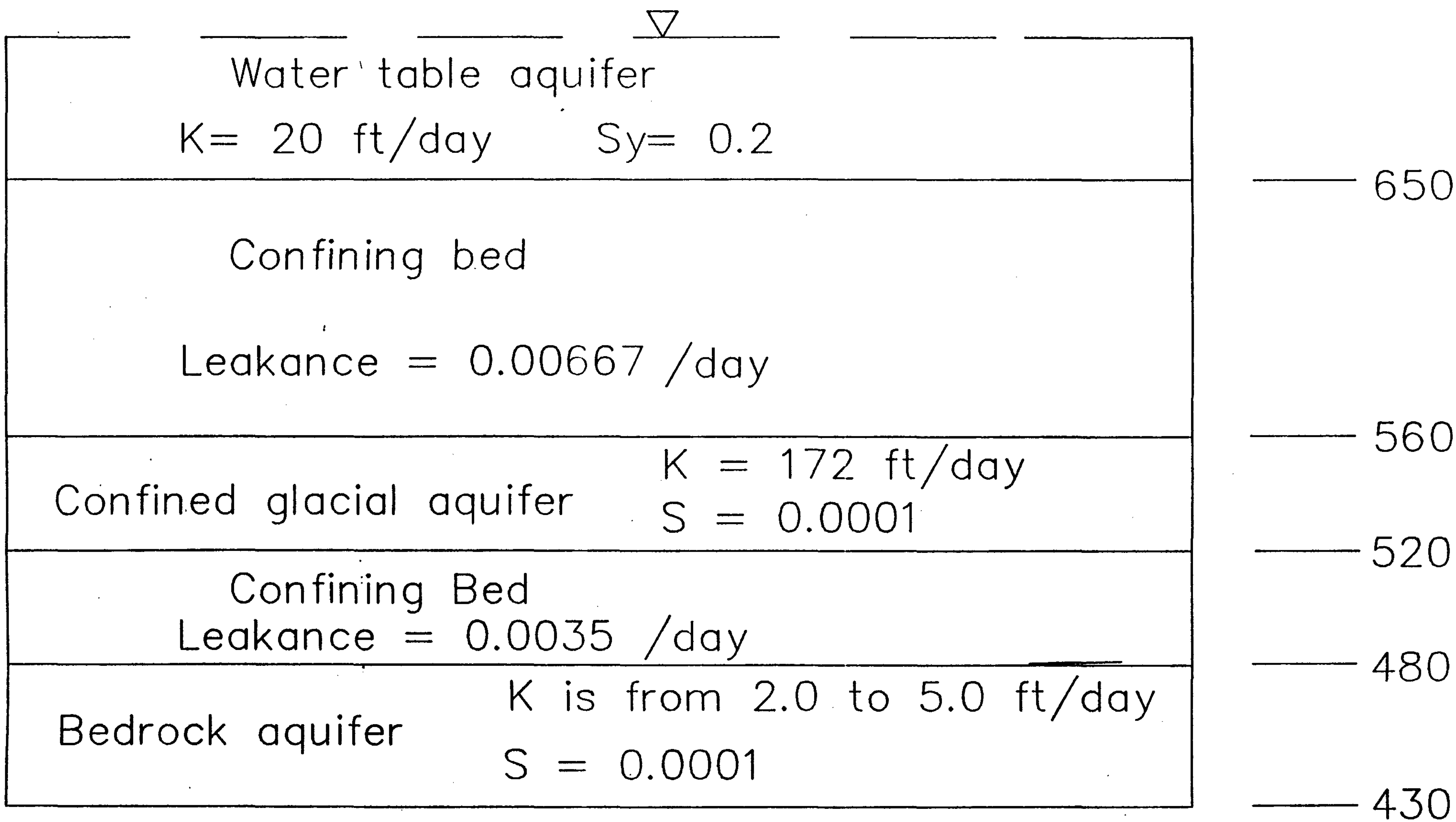

Figure III-4

Bedrock hydraulic conductivity was a difficult parameter to assign. The values ultimately used in the model were chosen during the calibration process. Values ranged from 2.5 ft/day on the slopes of the valley to 5.0 ft/day in the bedrock at the bottom of the valley. Figure III-5 shows the distribution of bedrock hydraulic conductivity in the model. These values were purely a result of the calibration. They are an order of magnitude larger than the values derived from specific capacities. The reason for this discrepancy may be that top of the fractured bedrock aquifer is relatively impermeable because the fractures are filled with the clayey products of weathering, while deeper fractures are open and highly transmissive. All of the available observation well data were from wells in the top of the bedrock aquifer. Another reason for the discrepancy between the values that produced a good calibration and the measured values is that the bedrock aquifer may actually be much thicker than the assumed thickness of 50 feet. If it was 250 feet thick, the values of hydraulic conductivity would have been five times smaller. The bedrock aquifer was always confined in all model runs. The flow in the bedrock aquifer could have been adjusted by changing aquifer thickness instead of changing hydraulic conductivity.

4. Streams

Green Pond Brook and Bear Swamp Brook were major features of the ground water model. Green Pond Brook flows down the longitudinal axis of the valley. Bear Swamp Brook enters the valley on the north side, flows immediately behind and underneath Building 24, and across the valley into Green Pond Brook within the modeled area. Bear Swamp Brook is in a pipe over parts of its length. It is only in connection with the water table aquifer in those grid nodes on Figure III-2 that are shaded.

Figure III-2 shows the grid nodes of layer 1, the water table aquifer, that were assumed to be in contact with these streams. River stages were interpolated from the topographic map and stage measurements made as part of <u>Ground-water Contamination in the Area of Building 24, Picatinny Arsenal, New Jersey</u> (Sargent et al, 1988). Green Pond Brook was assumed to be two feet deep throughout and Bear Swamp Brook was assumed to be one foot deep throughout. River conductances were developed by assuming the node conductance was proportional to the length of the river in

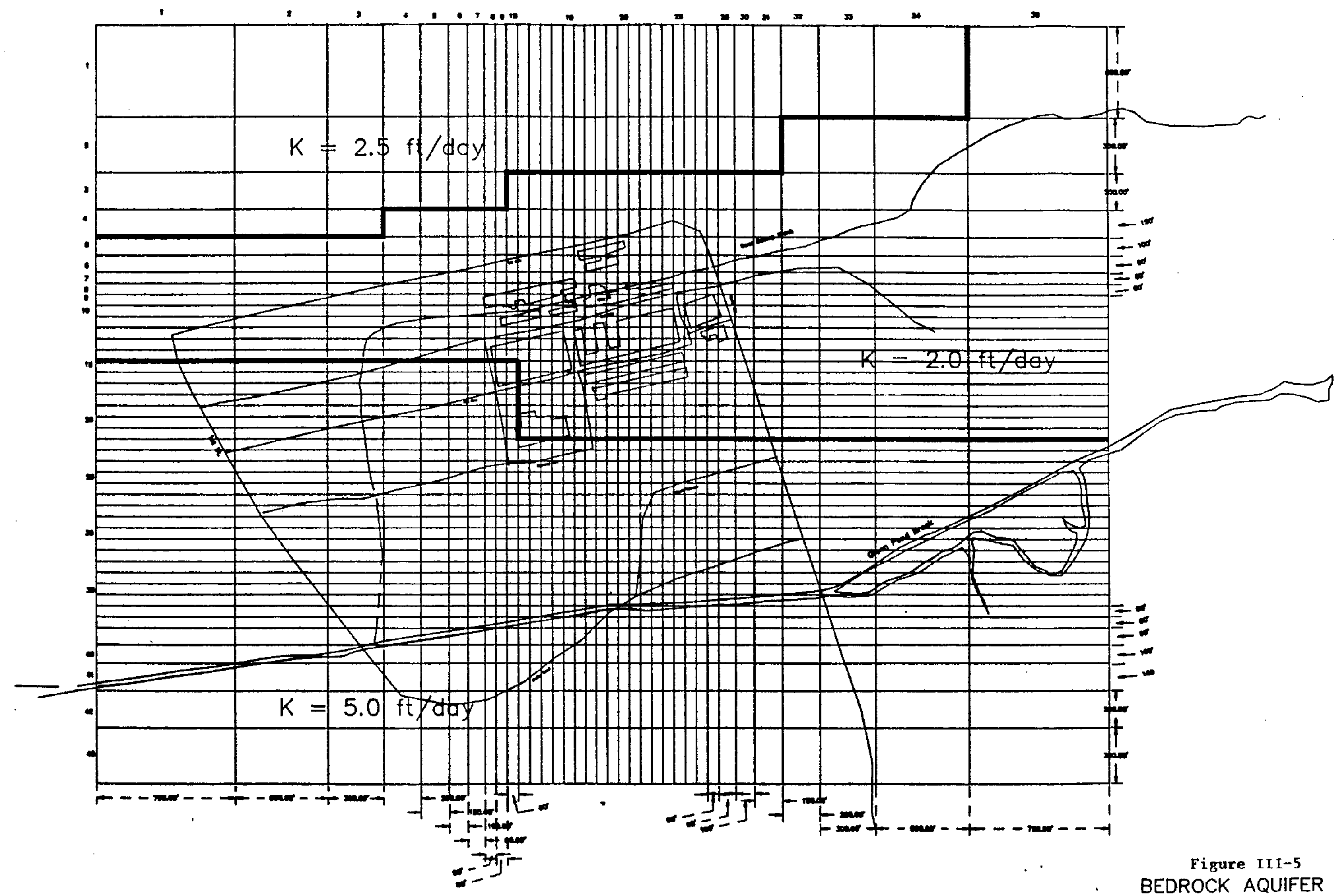

Figure III-5
BEDROCK AQUIFER

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the node. The proportionality constant was developed during the calibration process. For Green Pond Brook, the constant was 166.67 ft^2/day per foot of river. For Bear Swamp Brook, the constant was 1.67 ft^2/day per foot of river. These values fit with the available information which indicates Green Pond Brook is a large gaining (effluent) stream in constant and intimate contact with the water table aquifer, while Bear Swamp Brook is a small stream perched above the water table aquifer.

5. Recharge

Recharge from infiltration into the aquifer is an essential input to the model. In this model, recharge is the net recharge resulting from total recharge minus evapotranspiration from the water table.

The average annual precipitation for northern New Jersey is about 51 inches (NOAA, 1981). Average annual potential evapotranspiration is about 31.5 inches based on average pan evaporation of 45 inches/year (Linsley et al, 1958) and a pan coefficient of 0.7. The water table is close to the surface at this site so actual evapotranspiration is probably close to potential. Much of the site is paved so runoff would be a significant fraction of the annual water budget but this effect will be partly offset by the fact that there are numerous storm drains beneath the paved areas. These old storm drains may actually increase the recharge from paved areas since the pavement prevents evaporation from the soil. Values of recharge between 10 and 15 inches/year were used in the calibration process. Fourteen inches/year was chosen as the most suitable value.

6. Initial heads

The flow model was calibrated assuming that steady state conditions were present in the simulated system. Thus, model results are not dependant on initial head conditions. The input head data is used, however, for setting the elevations of constant head nodes. Adjustment of the constant head nodes at the boundaries of the model was an important element of the model calibration.

The approach to defining the initial heads was to perform a detailed mapping of the heads based on the available data and interpolate these data onto the model grid. A simple BASIC program, XDAT2, was written to assist in this task. This program allows the user to analyze spatially distributed data. Means and standard deviations may be computed. A linear regression analysis may be performed to find the trend in the data. The resulting trend surface equation may be used in a nondirectional inverse distance squared weighting procedure to interpolate

the values at grid nodes of a model grid. The resulting array of values may be output to a file in a format for input to the MODFLOW model.

There were 47 observation wells with static water levels in the water table aquifer. The water table elevations were found to have a statistically significant linear trend in space. The following equation fit the data.

head = 680.7173 + 9.56E-4 x + 3.97E-3 y

where
head = elevation of water table (ft)
x = distance from lower left corner of model grid along columns (ft)
y = distance from lower left corner of model grid along rows (ft)

The coefficient of determination (r^2) for this regression equation was .86. The F coefficient was 88.9 which indicates the significance of the correlation was very high.

This equation was used in the data analysis program to create the array of initial input heads over the model grid. The program goes through the grid node by node. At the middle of each node, the three closest actual observation wells were found, and combined with the result from the equation above using an inverse-distance squared formula. The head predicted by the linear regression equation was assumed to be 500 feet from the grid point. This procedure provides an accurate methodology for assigning initial head values to grid nodes. Where there are no data, the value predicted by the linear regression equation is used. Where there are close data points (closer than 500 feet in this case), the actual data values are used. The results of this analysis are shown on Figure III-6.

It was not possible to use the same procedure for the confined glacial aquifer because there were not enough observation wells in this aquifer. Instead of using actual well data, the potentiometric surface map from Sargent et al (1988) was digitized and these data analyzed. The following equation fit the data.

head = 683.4831 + 8.15E-4 x + 2.82E-3 y

where
head = elevation of potentiometric surface in confined glacial aquifer (ft)

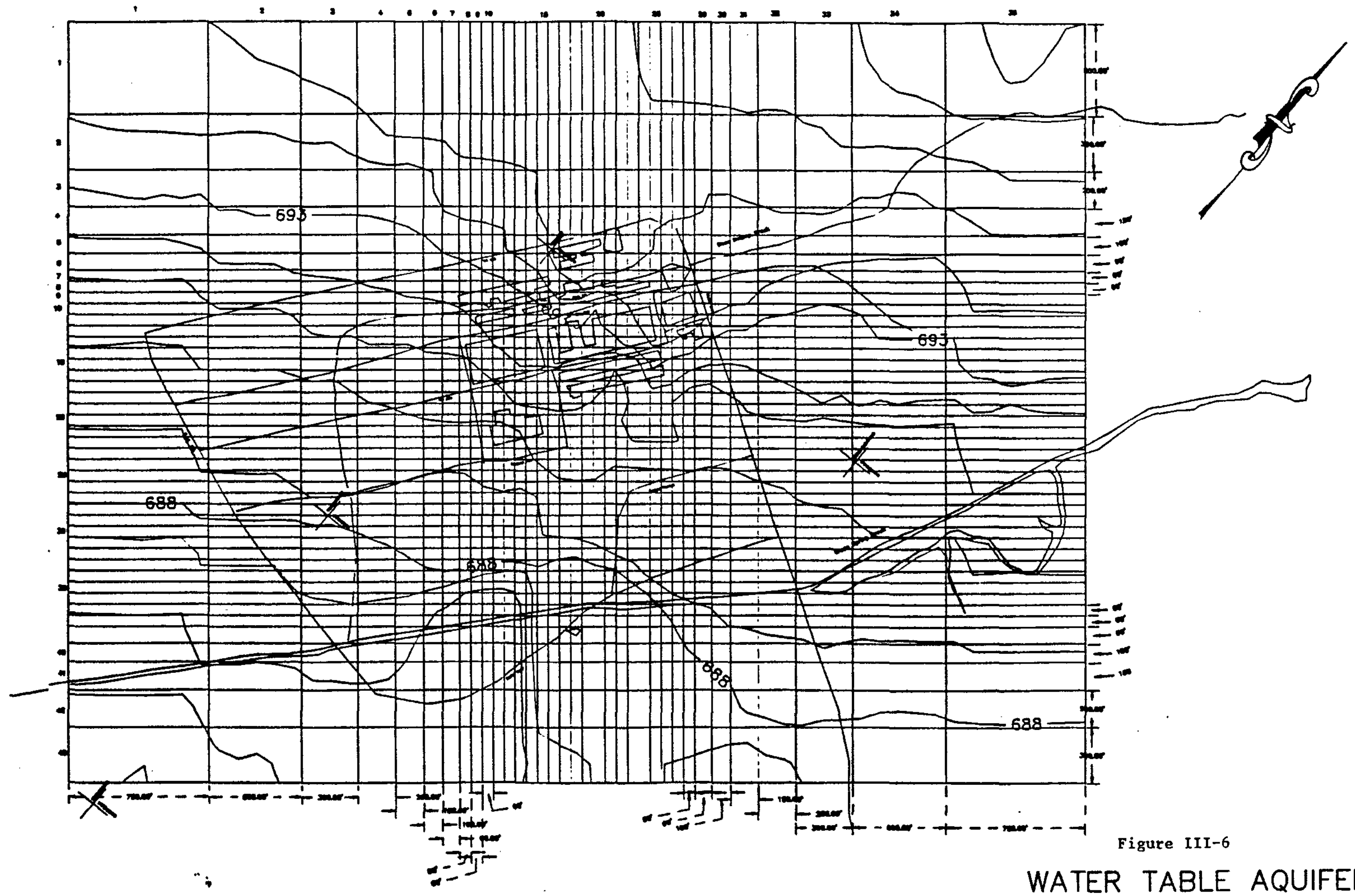

Figure III-6

WATER TABLE AQUIFER

PICATINNY ARSENAL NEW JERSEY

DEVELOP DOCUMENTATION/PREPARE REMEDIAL ACTION CONCEPT PLAN FOR THE BLDG 24 CONTAMINATION PLUME

INITIAL HEAD FOR LAYER 1

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(301) 461-9920

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The coefficient of determination (r^2) for this regression equation was .65. The F coefficient was 34.9 which indicates the significance of the correlation was very high. The array of initial heads in the confined glacial aquifer was computed using the same procedure that was used in the water table aquifer. The results of this analysis are shown on Figure III-7.

The bedrock aquifer data were also insufficient for an analysis of actual data. The potentiometric surface map shown in Sargent et al (1988) was used. The same procedure that was used for the confined glacial aquifer was used for the bedrock aquifer. The results of this regression and interpolation, however, did not result in a reasonable potentiometric surface for the bedrock aquifer. It was necessary to manually assign the head values to the constant head nodes surrounding the bedrock aquifer grid based on the topography of the site. The bedrock aquifer is assumed to be a shallow mantle of fractured rock that overlies the relatively unfractured and impervious bedrock. This assumption leads to the assumption that heads in the bedrock aquifer on the valley sides are relatively close to the land surface where there is no glacial till. Water falls on the hillsides, infiltrates to the fractured layer of bedrock, and flows down the hillside to the valley. There is no site specific data to prove that this interpretation is correct, but it is consistent with modern concepts regarding regional ground water flow patterns (Freeze and Cherry, 1979). The results of this analysis are shown on Figure III-8.

B. Flow Model Calibration to steady state

The objective of the calibration process was to develop a steady state flow model that represented the average long term position of the water table and underlying potentiometric surfaces in the aquifers at the Building 24 site. The previous discussion has focused on the input parameters. The various simulations performed and the adjustments made to the model will be discussed in this section of the report.

Calibration involves the matching of model results against real data until the "fit" is adequate for the purposes of the study. The process is typically a nonmechanical, and nonunique process that relies heavily on the analysts judgment. There are many data inputs to a three dimensional ground water flow model. Some data inputs are known with some degree of precision (such as river location); others (such as bedrock hydraulic conductivity) could vary over a wide range of values. The analysts job is to vary the input parameters in a realistic manner so the model output matches the real data.

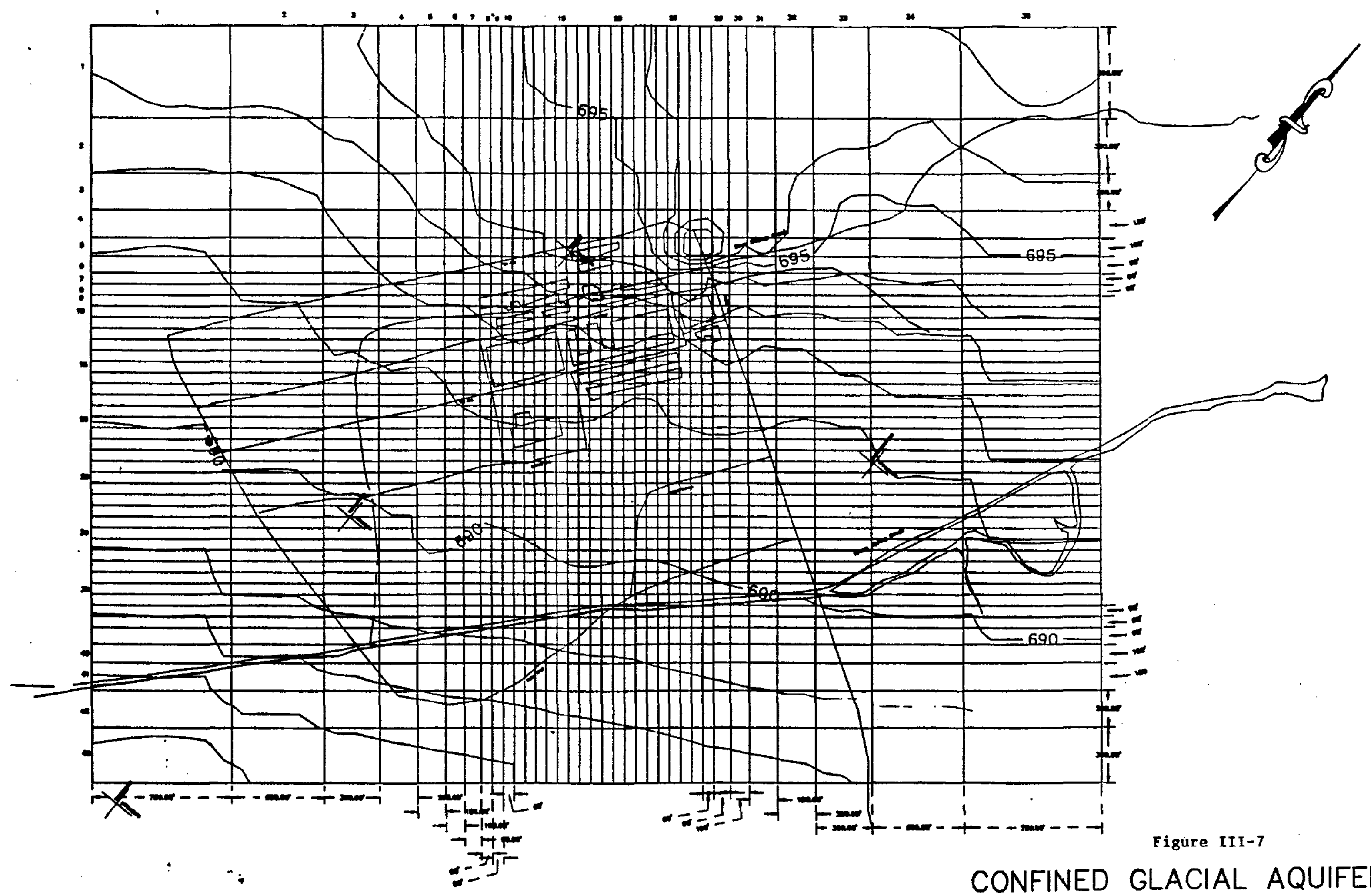

Figure III-7

CONFINED GLACIAL AQUIFER

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INITIAL HEAD FOR LAYER 2

REVISIONS

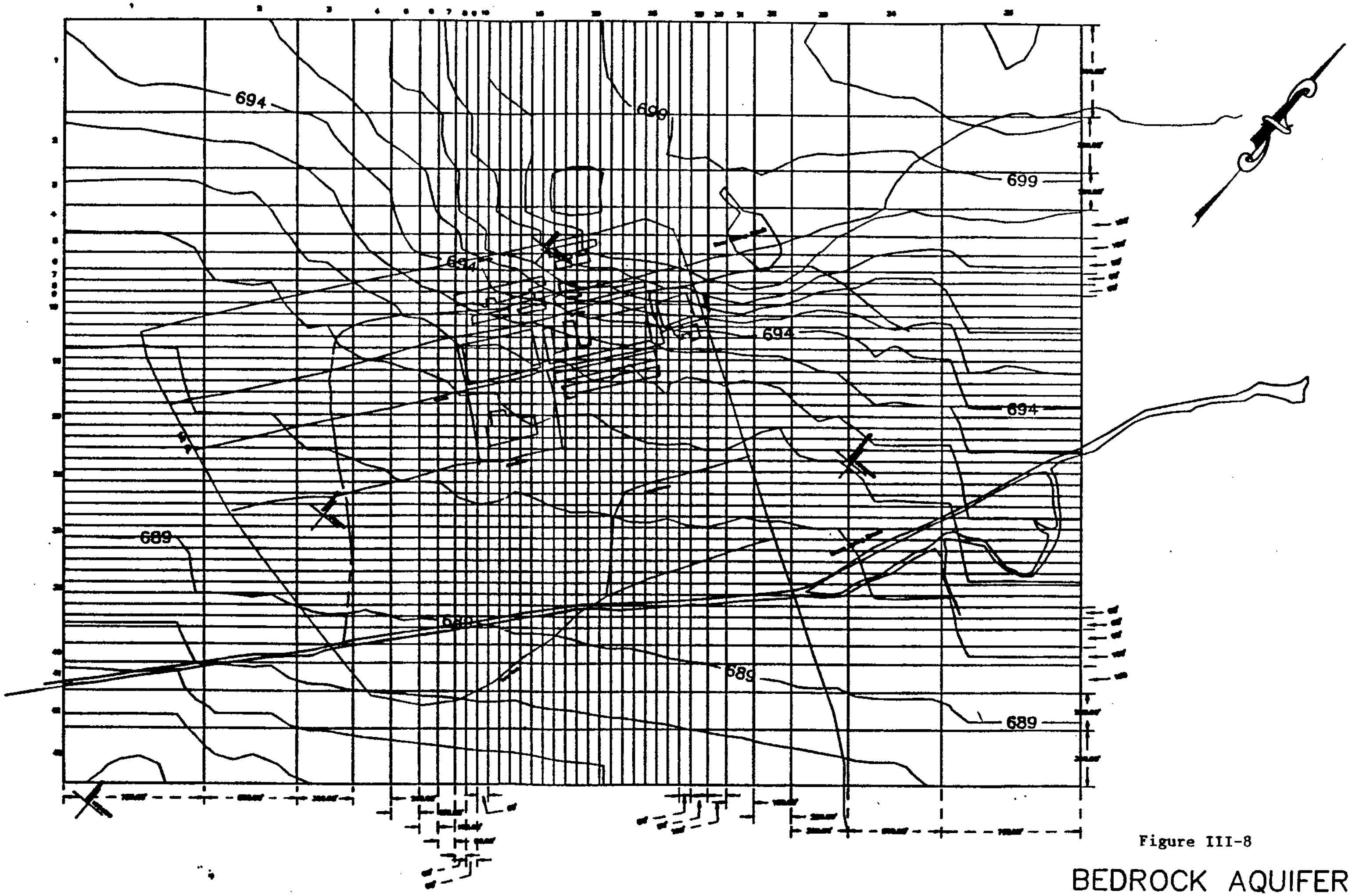

Figure III-8

BEDROCK AQUIFER

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DEVELOP DOCUMENTATION/PREPARE REMEDIAL ACTION CONCEPT PLAN FOR THE BLDG.24 CONTAMINATION PLUME
INITIAL HEAD IN LAYER 3

Two kinds of data were used to calibrate the MODFLOW model at the Building 24 site at the Picatinny Arsenal. There were aquifer head data in the Sargent et al report (1988) from September 1987. This report also contained interpretations of the water table and potentiometric surfaces in the different aquifers. The decision was made to match model results to the actual well water level data from September 1987. A short Fortran program was written to take model output data and compute the differences between the model predictions and well water levels. A list of wells, column and row locations, and elevations was prepared. Where there was more than one well in a single model grid, well data were averaged together.

The second kind of data used to calibrate the model were the stream flow measurements on Bear Swamp Brook and Green Pond Brook (Sargent et al, 1988). The predicted gain or loss by these streams was compared to the differences in measured flow along the streams.

Many parameters were varied throughout the calibration process but relatively few were changed in any significant manner. The first parameter that was changed was the initial distribution of head in the bedrock aquifer. The input based on the bedrock aquifer potentiometric surface map in Sargent et al (1988) was clearly wrong; the head values were much too low at the sides of the valley. A new distribution of head at the constant head nodes was prepared that reflected the topography of the valley. The initial value of bedrock hydraulic conductivity tried was about 3 ft/day. The comparison of bedrock aquifer head to bedrock well data showed, however, that there was too little gradient across most of the model. Then, different zones of hydraulic conductivity in the bedrock aquifer were tried, along with continued adjustment of the constant head boundary in the bedrock aquifer, particularly at the downstream end of model where well 39-1 was. A good calibration was achieved with an average error of 0.19 feet and a root mean-square error of 1.77 feet over 41 wells.

This calibration yielded a flow direction, however, with a considerably larger down valley component than exhibited by the TCE plume. This result was based on the observed water levels in wells 39-1 and 39-2, which are along Green Pond Brook downstream of the First Ave crossing. Well 39-1 is in the bottom of the confined glacial aquifer, or possibly in the confining layer between the confined glacial aquifer and the bedrock aquifer. The observed level in this well showed that ground water was flowing from the water table aquifer and Green Pond Brook down into the lower aquifers rather than the typical pattern of water flowing up from the bedrock into the water table aquifer and the stream. Conversations with Pierre Sargent (USGS, Trenton, NJ) indicated that the September 1987 water levels reported

for wells 39-1 and 39-2 were anomalous, and later measurements at these wells indicated water levels over fifteen feet higher.

Based on this information, the model was recalibrated. The recalibration went smoothly. New values of initial head for the bedrock aquifer were assumed. Numerous changes were made in the distribution of bedrock aquifer hydraulic conductivity. Eventually, a suitable set of values were found (see Figure III-4) and the model was judged to be adequately calibrated. The average error across 41 wells was 0.12 feet and the root mean-square error was 1.76 feet. Table III-3 shows the results of the comparison for each node and statistics for each layer of the model. Figures III-9, III-10, and III-11 show the calibrated water levels for the water table aquifer, confined glacial aquifer, and bedrock aquifer, respectively. The model predicted seepage to Green Pond Brook of 0.696 cfs. The same reach of Green Pond Brook had measured seepage of 0.68 cfs. The model predicted seepage from Bear Swamp Brook of 0.059 cfs. The same reach of Bear Swamp Brook had a measured seepage loss of 0.051 cfs.

Table III-3
Statistics for Flow Model Calibration

I	J	K	Well Head	Model Head	Difference	Well
7	30	1	689.54	689.43	-.11	I-2
7	31	1	687.80	689.16	1.36	I
8	17	1	690.55	691.72	1.17	65-4
9	38	1	685.32	685.23	-.09	41-4,5
10	39	1	685.96	686.24	.28	41-3
11	24	1	689.30	690.88	1.58	H-4
13	11	1	692.30	692.82	.52	64-1
13	29	1	688.83	689.95	1.12	112-9,10
15	12	1	693.69	692.76	-.93	9-D
17	11	1	693.56	692.96	-.60	9-E
17	12	1	692.00	692.83	.83	31-1
17	28	1	689.12	690.31	1.19	112-6,7,
17	38	1	688.30	686.44	-1.86	41-1,2
18	8	1	696.10	693.39	-2.71	9-C
18	10	1	693.10	693.13	.03	9-B
18	16	1	691.80	692.34	.54	CAF-2
18	17	1	691.72	692.21	.49	CAF-6
18	23	1	690.40	691.34	.94	92-3,4,5
18	36	1	686.90	686.51	-.39	41-8,9
19	11	1	692.30	693.03	.73	31-3A
20	9	1	693.00	693.32	.32	9-A
21	6	1	696.36	693.57	-2.79	10-3
21	18	1	690.60	692.16	1.56	130-3
21	28	1	689.39	690.37	.98	112-3,4,
23	12	1	692.37	692.99	.62	31-2A
23	16	1	690.60	692.48	1.88	34-1
24	19	1	691.20	692.08	.88	111-1,2
25	12	1	694.57	693.03	-1.54	31-5
25	15	1	693.41	692.64	-.77	34-2
26	8	1	693.50	693.54	.04	24-1
26	15	1	692.32	692.66	.34	CAF-5
27	29	1	689.61	690.05	.44	112-1,2
29	18	1	690.10	692.26	2.16	129-OBS
2	40	2	689.66	686.16	-3.50	39-1
8	17	2	695.80	691.33	-4.47	65-3
11	24	2	689.54	690.83	1.29	H-3
19	16	2	689.80	692.03	2.23	CAF-4,3
8	17	3	688.20	691.39	3.19	65-1,2
11	24	3	687.70	690.92	3.22	H-2
19	17	3	696.40	691.99	-4.41	CAF-1
21	6	3	697.90	697.22	-.68	10-3A

LAYER	WELLS	AVG DIFFERENCE	RMS
1	33	.25	1.20
2	4	-1.11	3.12
3	4	.33	3.18
TOTAL	41	.12	1.76

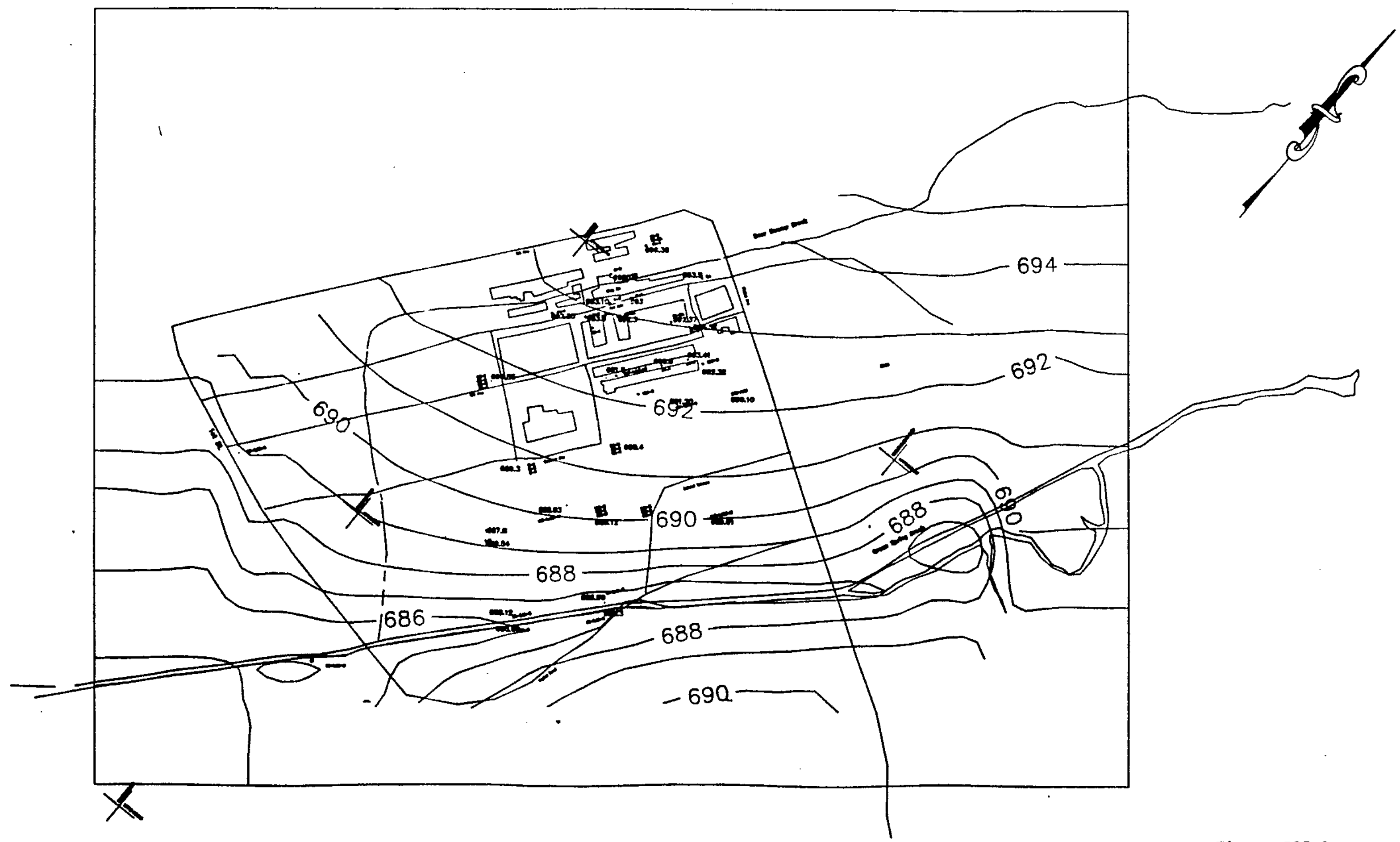

Figure III-9

WATER TABLE AQUIFER

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Calibrated Flow Model Water Table — Layer 1

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DRAWN	BHK
CHECKED	
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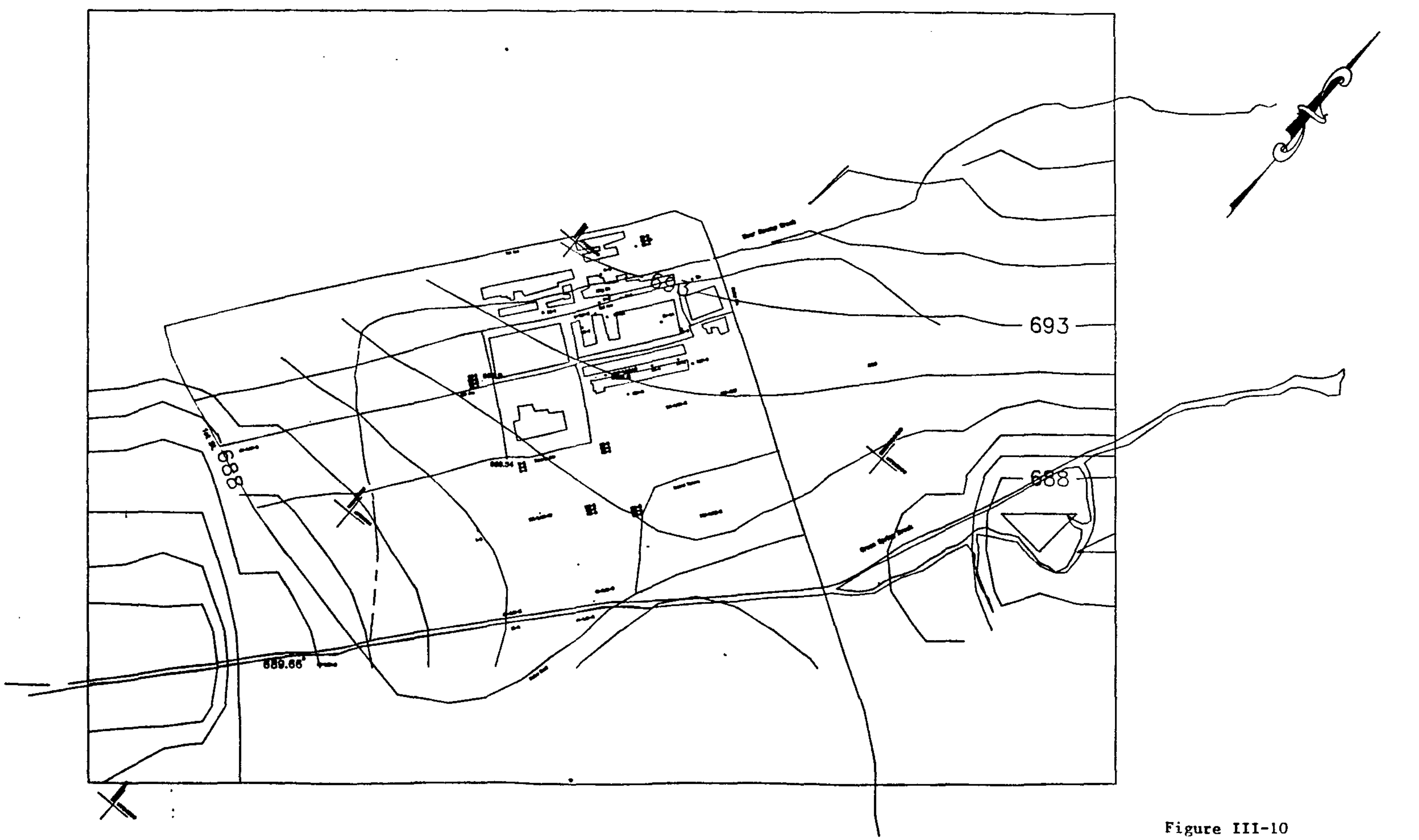

Figure III-10

CONFINED GLACIAL AQUIFER

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Calibrated Flow Model Confined Glacial Aquifer Head – Layer 3

SCALE 1"=600'

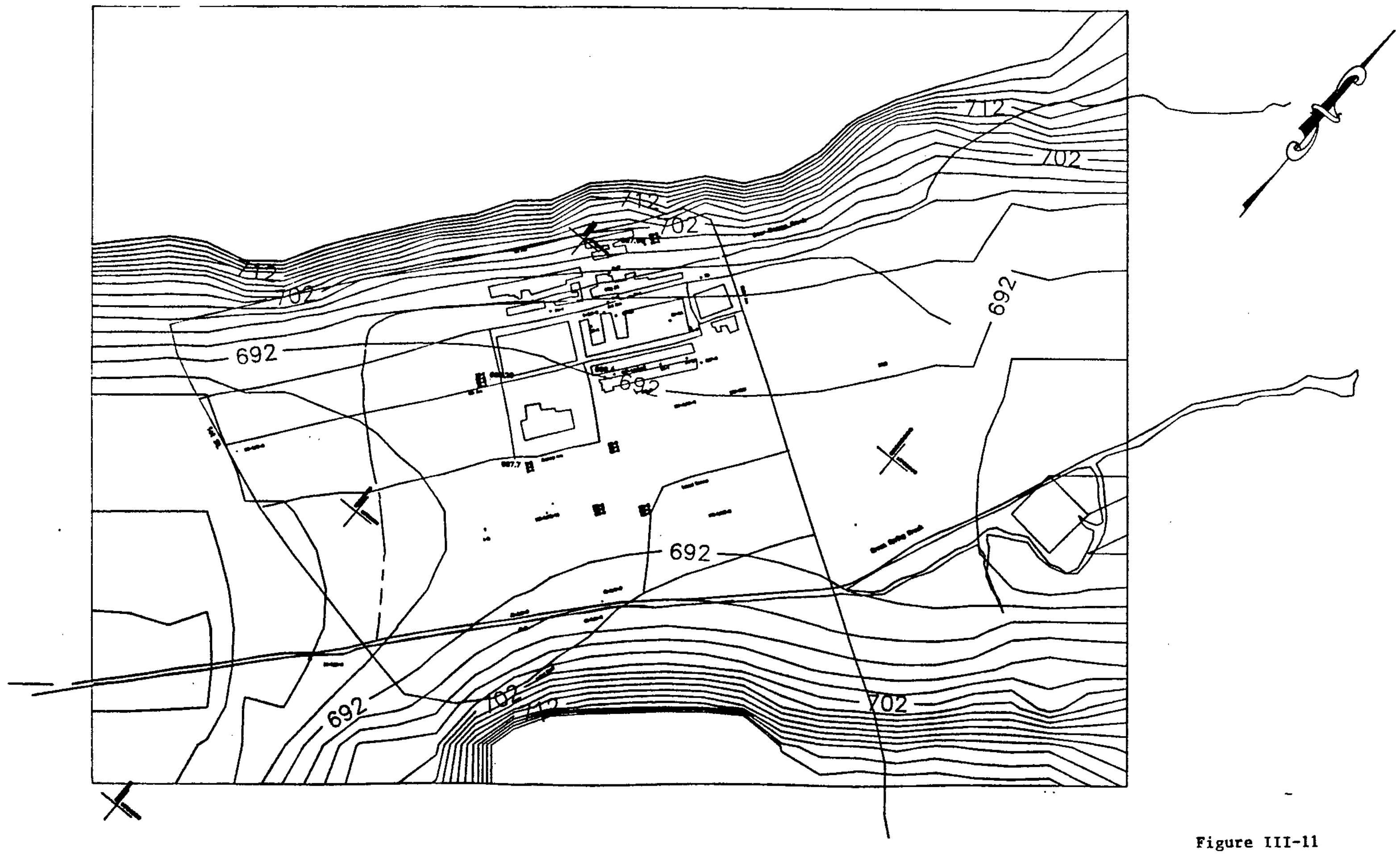

Figure III-11

BEDROCK AQUIFER

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Calibrated Flow Model Bedrock Aquifer Head – Layer 3

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C. Solute Transport Modeling

1. Introduction

The previously described three dimensional, random walk, solute transport model was used to simulate trichloroethylene (TCE) concentrations at the Building 24 site at the Picatinny Arsenal in New Jersey. The model was used to test alternative remedial action plans. Three scenarios were initially designed: a no action scenario, where the natural flow of ground water in the calibrated steady state flow model was used to flush contamination from the aquifers; a collector well only scenario, where collector wells were used to collect the TCE and form a flow barrier between Building 24 and Green Pond Brook; and an injection well scenario, where collector wells and injection wells were used to speed the rate of aquifer cleanup over that achievable with collector wells alone.

2. Model Setup

a. Grid

A subset of the flow model grid was used for solute transport simulation. Only the area of the grid with the 60 foot grid spacing was used for solute transport simulation. The solute transport model grid was from column 8 to column 28 and from row 7 to row 38 (see Figure III-2). This area included all of the TCE plume attributable to Building 24 and the area of the water table aquifer where the TCE plume is likely to travel in future years.

b. Aquifer characteristics

The RAND3D model uses the velocity vectors computed by the PREMOD3D preprocessor based on output from the MODFLOW finite difference flow model. Thus, RAND3D is dependant on the aquifer characteristics assumed for the MODFLOW model. The RAND3D model requires some additional data input on aquifer characteristics.

There were no field data available from which the correct value of porosity could be determined. Sargent et al (1988) assumed a value of 0.25 or 0.3 in their computations of seepage velocity.

The effective porosity of all layers in the model was assumed to be 0.2. This is a typical value for a sand and gravel aquifer. Effective porosity is frequently smaller than measured porosity because some intergranular flow paths are dead end pores. The chosen value should be applicable to the water table aquifer and the confined glacial aquifer. This value may be large for the bedrock aquifer, but there is little contamination in the bedrock aquifer, so this

shortcoming is not important to the modeling results. It may be large for the confining layers of the model, but reasonable results were obtained. Smaller values of porosity resulted in excessive vertical velocities in the confining layers.

There were no field data available on which to base the dispersivity constants. Dispersion is a topic of current controversy in ground water modeling. Originally, dispersion was assumed to be a function of mechanical mixing. Dispersion was assumed to be a linear function of velocity, with the constant of this function known as dispersivity. In recent years, the dispersion phenomena has been used in ground water solute transport models to account for the small scale heterogeneity of the aquifer. The functional form of the dispersion equation may not be linear as previously assumed, but increase with distance, possibly to some asymptotic value (Molz, Guven and Melville, 1983). The RAND3D model assumes a traditional constant dispersivity value where dispersion is a linear function of velocity. Values were chosen based on analytical simulations of the TCE plume between Building 24 and Green Pond Brook. Assuming a small point source, and present day ground water velocities, a transverse dispersivity of approximately 10 feet was necessary to get the existing plume width. Assuming a source the width of Building 24, a transverse dispersivity of approximately three feet was necessary to get the existing plume width. The smaller value was chosen for use in all simulations. Longitudinal dispersivity is frequently assumed to be three to ten times transverse dispersivity. A longitudinal dispersivity of ten feet was used in all simulations. Vertical dispersivity is even more difficult to select than the horizontal dispersivities since three dimensional solute transport models are relatively uncommon. Experience with three dimensional solute transport modeling shows that vertical dispersivity should be small, approaching zero, since large values yield unreasonable results (Thomas Prickett, 1988). A value of 0.1 feet was used in all simulations.

c. Initial Distribution of TCE

The source of the Building 24 contamination is believed to be the unlined lagoons behind the building. From at least 1960 to 1981, the metal-plating operation in Building 24 discharged wastewater into two lagoons behind the building. These lagoons had sand bottoms and permitted the infiltration of the wastewater into the ground water (Sargent et al, 1988). Trichloroethylene was one of the degreasing solvents used in Building 24 and is known to be a major pollutant in the wastewater. In 1981, the seepage lagoons were replaced by concrete settling basins. During reconstruction of the basins, 532 cubic feet of contaminated soil was removed from the site.

Another potential source of TCE contamination from Building 24 was a relief line connected to the degreaser and to an overflow pit (dry well) in front of the building. The relief line was designed as a safety feature to prevent the accidental overflow of solvent in the degreaser tank. Although no overflow event is known to have occurred, it is believed that condensation of TCE vapor within the pipe during the operation of the degreaser may have caused the release of a significant quantity of TCE to the overflow pit. The relief line was capped in 1985 (Sargent et al, 1988).

Trichloroethylene was replaced by 1,1,1-trichloroethane as a degreasing agent in 1983 (Sargent et al, 1988).

Based on the above data, one would anticipate that releases of TCE to the environment from Building 24 ceased in the early 1980's. The assumption was made that all sources of TCE contamination had ceased contributing TCE to the water table aquifer at the beginning of simulations. This assumption may not be true. There is probably TCE in the unsaturated zone near Building 24 that continues to travel downward to the saturated zone when recharge occurs. If the release of TCE to the saturated zone of the water table aquifer had stopped in the early 1980's, there would be little TCE in the vicinity of Building 24; the natural flow of ground water would have transported the TCE away from the building. Thus, a good case may be made for a continuing source of TCE to the water table aquifer at Building 24. There may also be unknown sources of TCE that are still contributing to the contamination problems in the aquifer. The results of the remedial action simulations assume no additional contribution of TCE, but the remedial actions are designed to be effective even if there are additional sources of TCE in the aquifer.

Sargent et al (1988) developed TCE concentration contours at three different elevations (650, 670 and 690 foot elevations) within the water table aquifer based on data collected during 1986 and 1987. These TCE concentration contours were used to prepare model input (see Figures 21, 22, and 23 of Sargent, 1988). The concentration contours were digitized into an AUTOCAD file. The concentration contours were exported from AUTOCAD into data files. Each data file was gridded on 60 foot square cells using the Golden Software SURFER program. A short BASIC program was prepared to combine the three grid files into a single file and assign particle locations. Each gridded concentration map was assigned a thickness. The total mass of TCE in the water table aquifer was computed assuming the bottom elevation of the aquifer as 650 feet and the top elevation as 692 feet. Each grid file was assigned an incremental depth. The thickness of the 650 foot elevation concentration map was assumed to be 10 feet. The thickness

of the 670 foot elevation concentration map was assumed to be 20 feet. The thickness of the 690 foot contour was assumed to be 12 feet. The mass of TCE within each grid cell was computed using a porosity of 0.2. The total mass in the aquifer was computed by summing the TCE mass in each cell. The total mass of TCE in the water table aquifer was computed to be 410 pounds. Actual particle locations were assigned and written to a file. The total mass of TCE was divided by the number of particles (selected as 9500) to find the particle weight. The calculated particle weight was 0.04314 pounds. The number of particles within each cell were computed. Particle locations within each cell were assigned randomly in three dimensions.

In some instances, the concentration in a grid cell is small and the computed cell mass is less than one particle. To avoid round-off errors, fractional particles are summed continuously and added to the mass of the next cell.

Given the total mass of TCE in water table aquifer, 410 pounds; the assumed porosity, 0.2; the number of particles, 9500; and the maximum grid cell volume, 72000 ft^3 (60*60*20); the minimum concentration represented by at least one particle was 46 ppb. Where concentrations less than this were present, particles were assigned when the fractional particle mass was summed into a full particle.

This procedure resulted in the starting TCE distribution shown in Figure III-12. Given the data processing to produce this map, it represents an idealized distribution of TCE in the water table aquifer.

No concentration contours were available for the confined glacial aquifer, however, wells within the aquifer have tested positive for TCE. Two wells completed in the confined glacial aquifer near the cafeteria (CAF-3 and CAF-4) have had recurring detectable TCE concentrations. One possibility for TCE in this area is that production well 130 caused downward movement of TCE into the confined glacial aquifer. Based on the average TCE concentration in this area, 200 ppb, and an assumed radius of 200 feet, the probable mass of TCE in the confined glacial aquifer was 3.13 lbs. Using the previously computed particle weight of 0.04314 lbs, the number of particles in the confined glacial aquifer for the simulation was calculated to be 73. These particles were distributed as a cylindrical slug source within the confined glacial aquifer around production well 130. Figure III-13 shows the initial concentration contours within this aquifer.

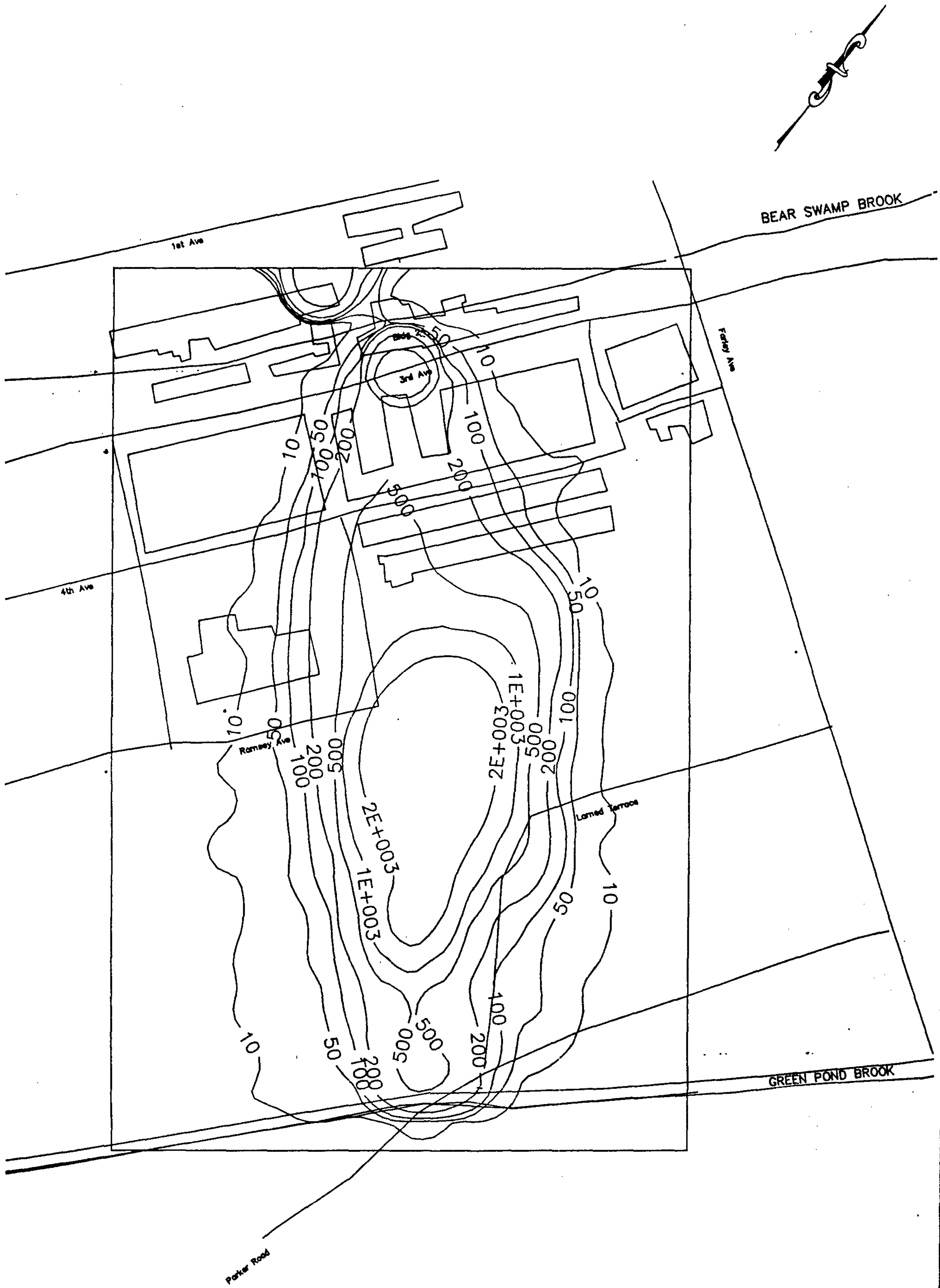
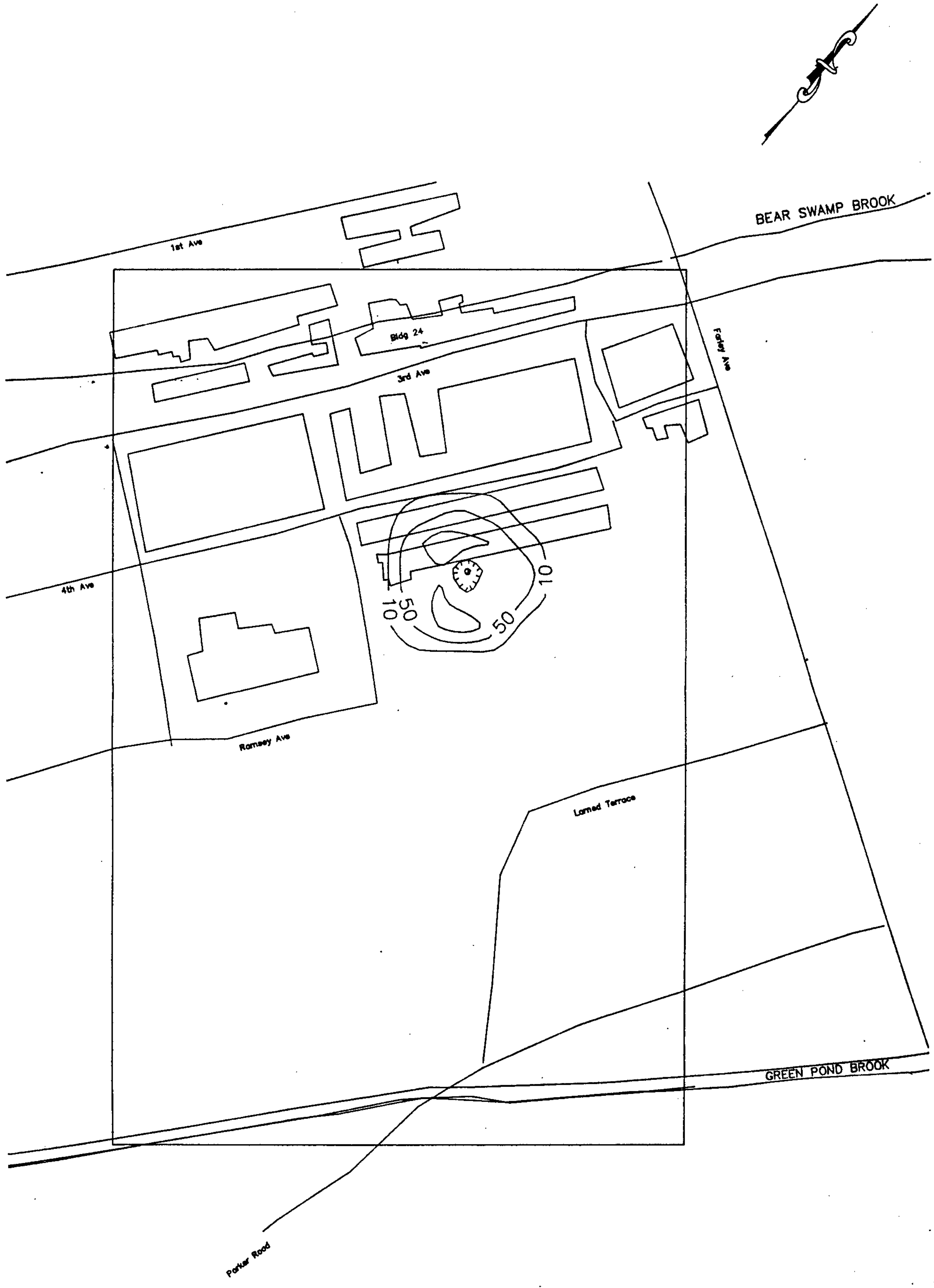


Figure III-12

WATER TABLE AQUIFER

DESIGNED DHK 2/89 DATE	ENGINEERING TECHNOLOGIES ASSOCIATES, INC.	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING
DRAWN PPM 2/89 DATE	ENGINEERS • PLANNERS • SURVEYORS	INITIAL TCE CONCENTRATION (ppb)
CHECKED DATE	3458 ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	SCALE 1"=200' CONTRACT NO. 8313.10 DATE 3/8/89 SHEET
APPROVED DATE		



CONFINED GLACIAL AQUIFER

Figure III-13

DESIGNED	DHK	2/89	
DRAWN	PPM	2/89	
CHECKED			
APPROVED			

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3458 ELLICOTT CENTER DRIVE SUITE 101
ELLICOTT CITY, MARYLAND 21043

PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

INITIAL TCE CONCENTRATION (ppb)
CONFINED ACQUIFER

SCALE	CONTRACT NO.	DATE	SHEET
1"=200'	8313.10	3/8/89	

d. Adsorption

Trichloroethylene is subject to adsorption in ground water aquifers (Karickhoff et al, 1979). At very small concentrations (which we have in this case), adsorption is commonly assumed to be a linear function of concentration, and reversible. Linear reversible adsorption results in the retardation of solute transport compared to the velocity of ground water. Adsorption of hydrophobic organic compounds is commonly assumed to be controlled by the amount of organic carbon in the aquifer, although it is also known that TCE adsorbs to clays (Johnson et al, 1989). The equation for retardation is:

$$R = 1 + K_d p/n$$

where
- R = retardation coefficient
- K_d = partition coefficient (ml/g)
- p = bulk density of aquifer material (g/ml)
- n = porosity

No data on adsorption or organic carbon concentrations were available for the Picatinny Arsenal. An initial attempt was made to deduce the retardation coefficient by examining trends in concentration data over time. It was hoped that peak concentrations in the TCE plume may have passed different observation wells at different times. The data were not sufficient for this type of analysis. The amounts of TCE discharged to the aquifer are unknown. Even the exact starting time at which TCE could have first been discharged to the environment from Building 24 is uncertain, although 1960 has been given as the earliest date of TCE use (Sargent et al, 1988). The only known fact is that TCE has reached Green Pond Brook from Building 24. If we assume the 1960 date is accurate, then it took no more than 26 years for TCE to travel 1700 feet from Building 24 to Green Pond Brook. If the seepage velocity is about 0.5 feet/day, then the retardation coefficient could be no more than 2.8.

The retardation coefficients input to the model were assumed to be one (no retardation) for the aquifer layers, and 1.5 in the confining layers. These are minimum values. The sensitivity analysis examined the impact of a larger retardation coefficient on the conclusions of the report.

e. Decay

Recent research has indicated the TCE will break down under anaerobic conditions in an aquifer (Barrio-Lage et al, 1987). The half-life of TCE under optimum conditions for biodegradation will be relatively small (on the order of days). Under less than ideal conditions, the half-life will

be much larger (several months), and under many conditions (aerobic conditions, low organic content, low microbial population) TCE may not be subject to biodegradation at all. The assumption was made for this project that there is no biodegradation, a first order decay rate of zero.

The shallow water table at the Picatinny Arsenal probably contains oxygen in small amounts. This small amount of oxygen probably inhibits anaerobic breakdown of TCE. The confined glacial aquifers and bedrock aquifers probably contain no oxygen, thus TCE is able to degrade in the deeper strata.

Trichloroethylene degrades to 1,2-dichloroethylene (DCE) and then to vinyl chloride (Kleopfer et al, 1985). Vinyl chloride is a known carcinogen. Degradation may have a detrimental impact on the water quality, rather than a desirable impact. If vinyl chloride is formed from TCE, one contaminant has been exchanged for another. The assumption of no degradation implies that the simulation may not be strictly of TCE, but rather TCE plus its degradation products. The initial distribution of TCE in the aquifer assumed 413 lbs or 1457 moles. Since each mole of TCE could form one mole of DCE and then one mole of vinyl chloride, the model could also be assumed be represent 311 lbs of DCE or 201 lbs of vinyl chloride. The results should be interpreted based on the possibility of these degradation products occurring.

3. Remedial Action Scenarios

a. Introduction

The objectives of the remedial action are to prevent TCE and other organic chemicals from reaching Green Pond Brook and to remove the contamination from the ground water. Green Pond Brook is a tributary of the Rockaway River, which flows into the Boonton Reservoir, which is the water supply for Jersey City. It is thus necessary to prevent contamination from entering the stream. It is also desirable to remove the contamination from the aquifer as quickly as possible.

The proposed remedial actions were designed to meet both of the above objectives. The remedial action had to prevent TCE from reaching Green Pond Brook. Given the uncertainty in the initial distribution of TCE in the aquifer and the probability of there being additional TCE entering the aquifer from the unsaturated zone or an unknown source, a prudent remedial action will form a barrier between Building 24 area and Green Pond Brook. Even if the assumptions in this report regarding TCE source and initial distribution are incorrect, the barrier will still prevent TCE (and other contaminants) from reaching Green Pond Brook.

b. No Action

The no action alternative simulates the flushing of the aquifer by the natural flow of ground water at the site. The RAND3D model was run for sixty years with velocity vectors resulting from the calibrated steady state flow model. All other parameters are as previously described. Figure III-14 shows the fractional removal of TCE from the aquifer by Green Pond Brook. After two years, 20 percent of the TCE has entered Green Pond Brook. After five years, 60 percent of the contamination has entered Green Pond Brook. After ten years, over 75 percent of the contamination has entered Green Pond Brook. After fifteen years, the water table aquifer is relatively clean, most of the remaining TCE is trapped in the confining layer between the water table aquifer and the confined glacial aquifer. After seventy years, 13 percent of the initial TCE is still in the aquifer system.

Figure III-15 shows the concentration of TCE in the ground water seeping into Green Pond Brook over time. This is an average concentration for the reach simulated in the solute transport model, approximately 1300 feet of stream channel. Concentrations increase to a peak of 83 ppb after four years. TCE concentrations in stream seepage decline; at the end of 12 years they are less than 5 ppb. Assuming an average flow for Green Spring Brook of about six cfs, the maximum instream concentration of TCE would be 5 ppb. This number is surprisingly close to the observed values of TCE in Green Pond Brook which are from 2 to 3 ppb (Sargent et al, 1988). Since the no action scenario is simulating present conditions, this similarity between simulated and observed in-stream TCE concentrations partially validates the model.

c. Initial Collector well scenario

A row of collector wells between Building 24 and Green Pond Brook in the water table aquifer provides for a barrier which will prevent TCE from flowing into Green Pond Brook, as well as a method of collecting contaminated ground water for treatment.

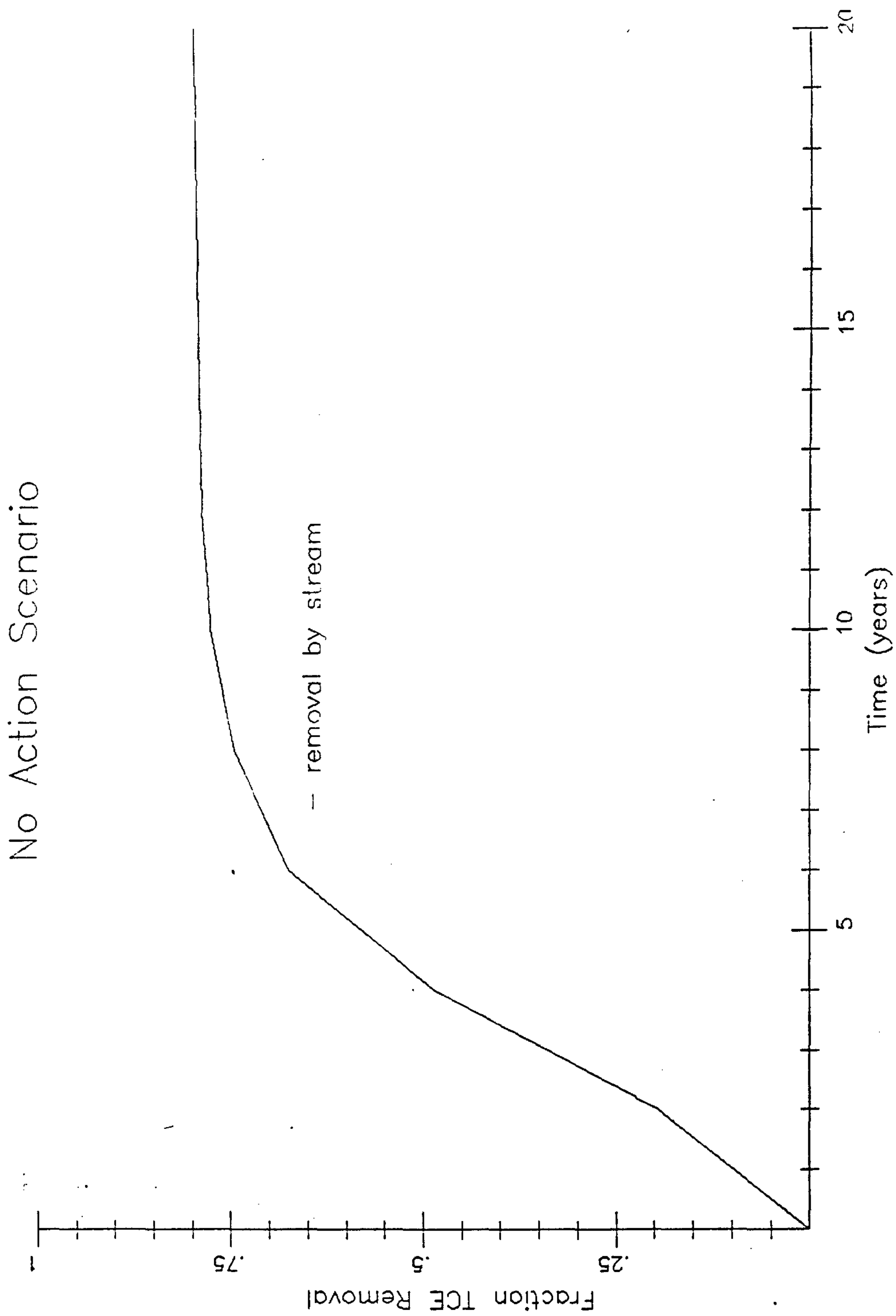

Figure III-14

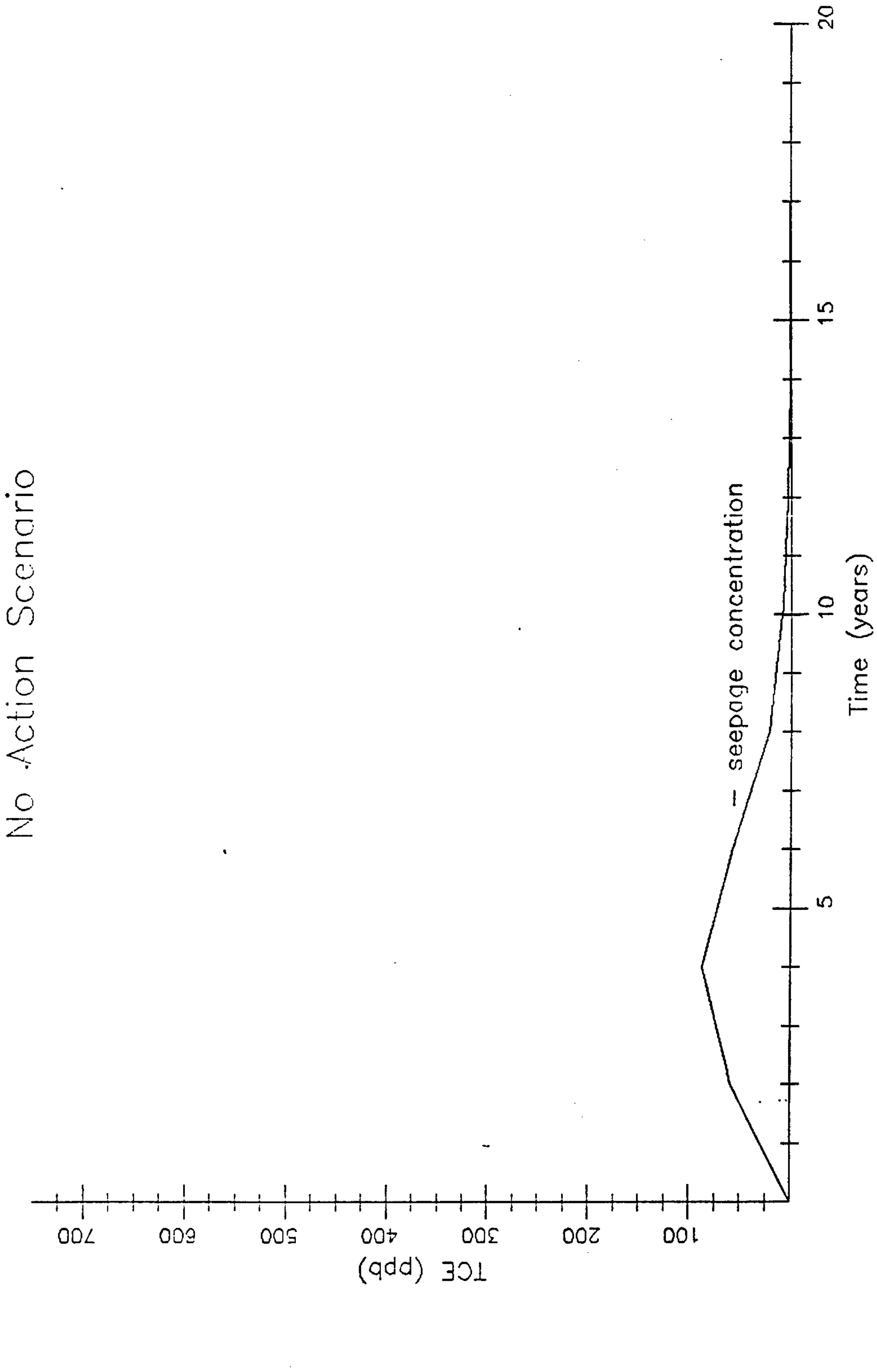

Figure III-15

A preliminary analytical solution was used to determine the spacing and pumping rates of the collector wells. A simple solution to the streamline function of a well in a uniform velocity field may be used to determine the maximum distance between collection wells so that all streamlines lead to a well. The equation is:

$$y = Q/4bu$$

(Harr, 1962)

where

- y = distance from well to stagnation point perpendicular to velocity field
- Q = pumping rate of well
- b = aquifer thickness
- u = Darcy velocity of flow, assumed to be in x direction

The water table aquifer was assumed to be a uniform, homogeneous aquifer with a hydraulic conductivity of 20 ft/day, a hydraulic gradient of 0.0044, and a saturated thickness of 40 feet. A well spacing of about 480 feet was selected after selecting possible well sites on the topographic map. The above equation was solved for the pumping rate, yielding 17.6 gpm. Pumping rates were chosen to be twice this theoretical value, 36 gpm, thus providing a factor of safety to account for leakage, and nonuniformity of the aquifer.

Well locations were chosen to span the delineated TCE plume (Sargent et al, 1988) at approximately the indicated spacing of 480 feet. The best place for the collector wells is in the golf course. Sites for the wells were chosen in the rough of the golf course at places where they should not interfere with play. Well sites may be moved 60 feet without having any adverse impact on the modeling predictions. Collector well 1 is located in the rough south of the 15th fairway. Collector well 2 is located in the rough south of the 15th fairway near the 12th tee. Collector well 3 is located east of Larned Terrace between the 16th and 17th fairways. Figure III-16 shows the locations of the wells.

The MODFLOW model was used to simulate the ground water flow impacts of the collector wells. The following well locations were used.

Well	Column	Row	Pumping Rate (ft^3/day)
1	9	27	6930
2	17	28	6930
3	23	30	6930

Each collector well was assumed to have a radius of 0.25 feet and fully penetrate the water table aquifer. The wells

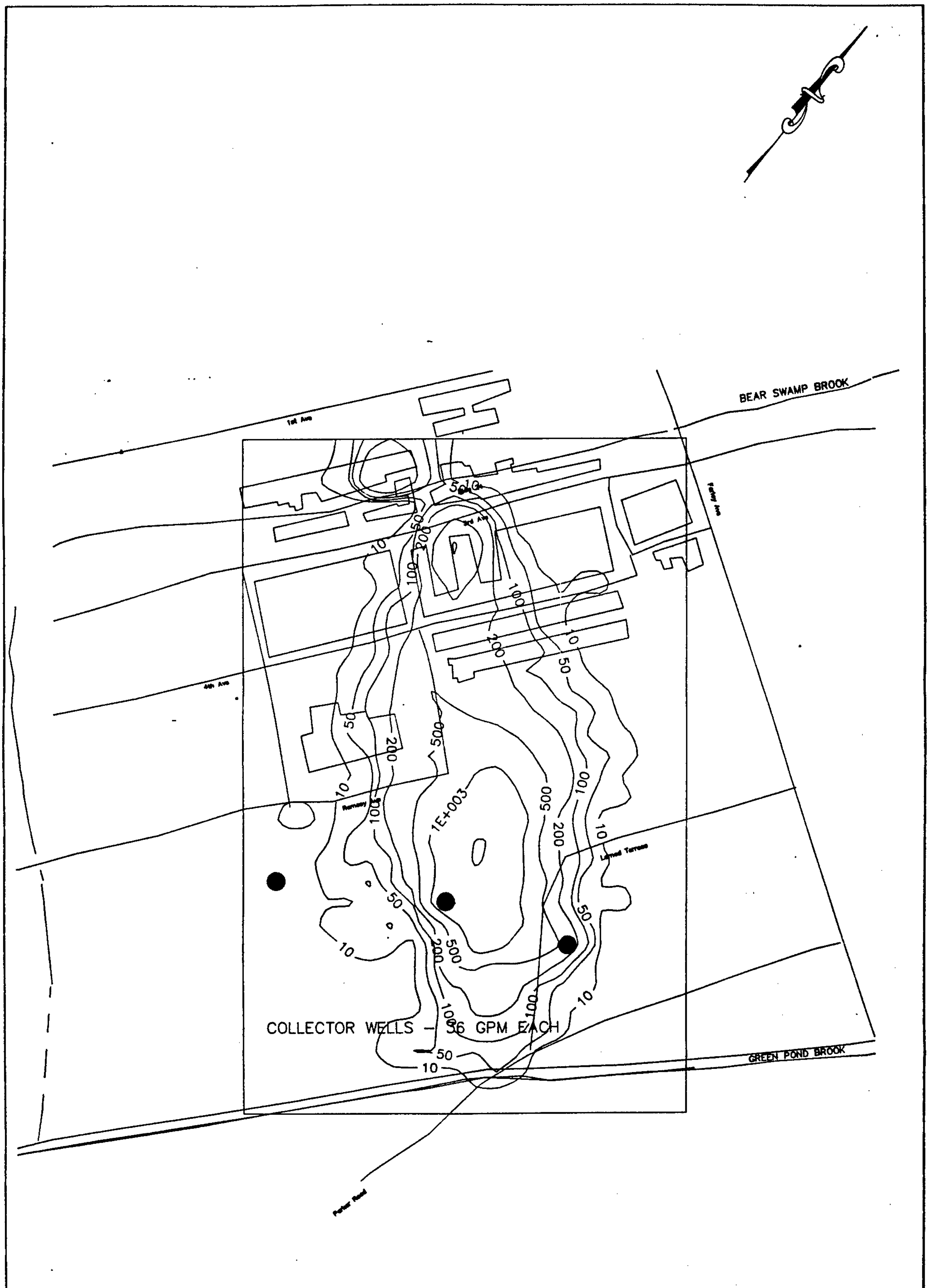

Figure III-16

DESIGNED	DHK 2/89
DRAWN	PPM 2/89
CHECKED	
APPROVED	

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ELLICOTT CITY, MARYLAND 21043

PICATINNY ARSENAL, N.J. GROUND WATER MODELING

COLLECTION WELL SCENARIO

TCE CONCENTRATIONS (ppb) — YEAR 1

SCALE: 1"=250 CONTRACT NO: 8313.10 DATE: 3/1/89 SHEET:

were assumed to be 100 percent efficient (no well loss). The flow model was run for five years with 60.833 day time steps. Steady state was reached at about two years. Figure III-17 shows the steady state position of the water table with the collector wells pumping continuously. Steady state well drawdowns are

Well	Drawdown (ft)
1	12.3
2	12.7
3	12.4

The collector wells cause less ground water to flow into Green Pond Brook. Stream depletion by the wells at steady state is 45 gpm, 1.8 percent of stream flow.

PREMOD3D was used to generate velocity files at intervals of 60.833 days. The resulting velocity files were input to RAND3D. For this initial remedial action scenario simulation a smaller number of particles and a larger particle weight were used. The particle weight was 0.08316 lbs. Forty-five hundred particles were used initially in the water table aquifer. No particles were started in the confined glacial aquifer. All other solute transport parameters were as discussed above. The model was run for fifteen years. Times steps of 60.833 days were used for the first three years to simulate a transient flow field. The remaining time steps were one year in length.

Figure III-18 shows the rate of TCE removal from the aquifer by the wells and the stream. After three years of pumping, 85 percent of the TCE has been removed from the aquifers, with 79 percent being removed by the collection wells and six percent entering Green Pond Brook. After six years of pumping, 91 percent of the TCE has been removed, 88 percent by the wells and six percent by the stream. At this point, the water table aquifer is almost free of contamination. TCE is still moving through the confining layer into the confined glacial aquifer at this time. The contamination moves rapidly through the confined glacial aquifer and begins to travel up through the confining layer under the collection wells. Travel through the confining layer is very slow, however, and at the end of fifteen years of simulation, approximately three percent of the initial contamination is still in the aquifer system. Figure III-16 shows the TCE concentrations in the water table aquifer after one year of pumping.

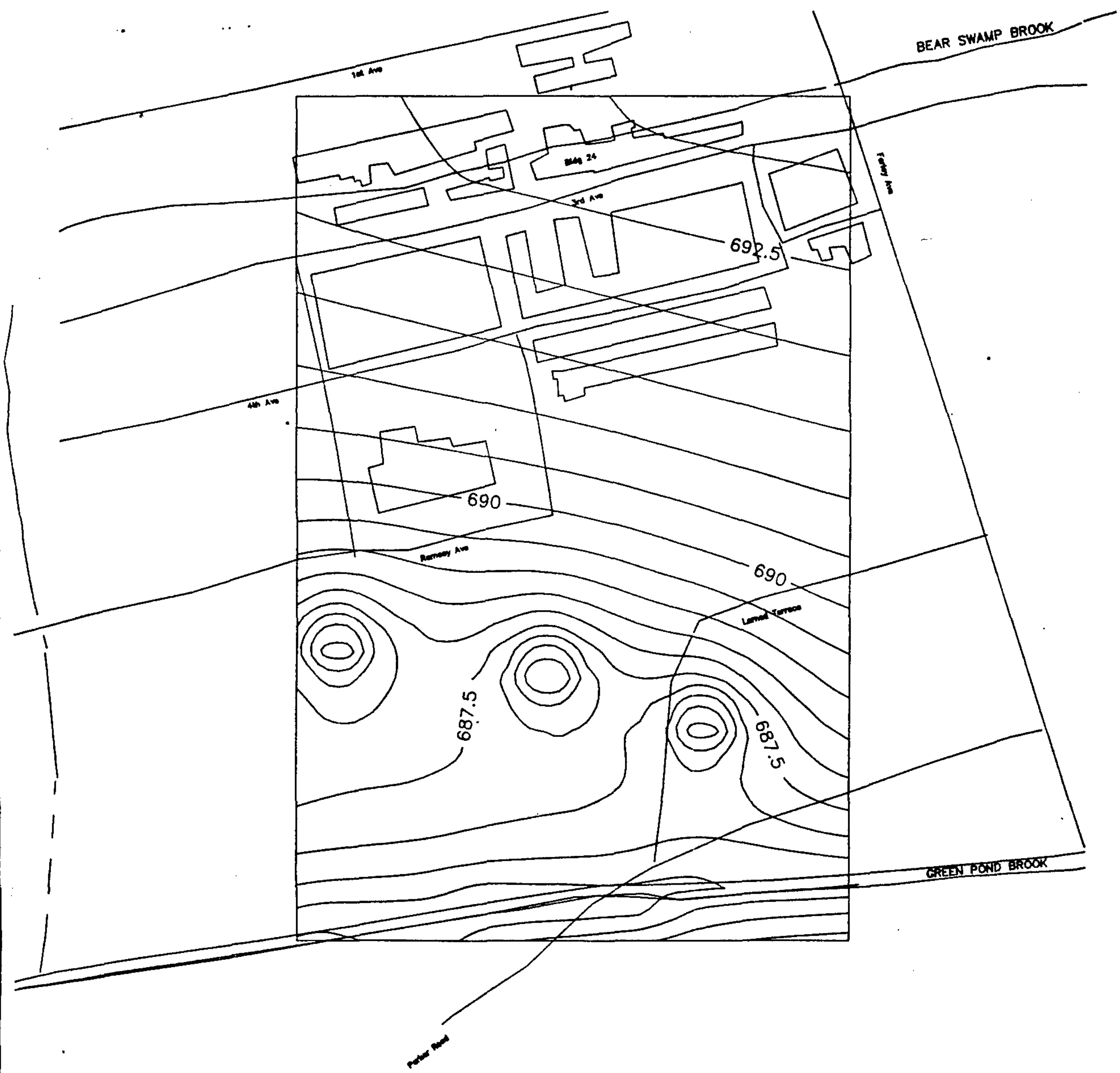

Figure III-17

DESIGNED	DHK	2/89	DATE
DRAWN	PPM	2/89	DATE
CHECKED			DATE
APPROVED			DATE

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PICATINNY ARSENAL, N.J. GROUND WATER MODELING

COLLECTION WELL SCENARIO

STEADY STATE WATER TABLE

SCALE: 1" = 250 | CONTRACT NO.: 8313.10 | DATE: 3/1/89 | SHEET:

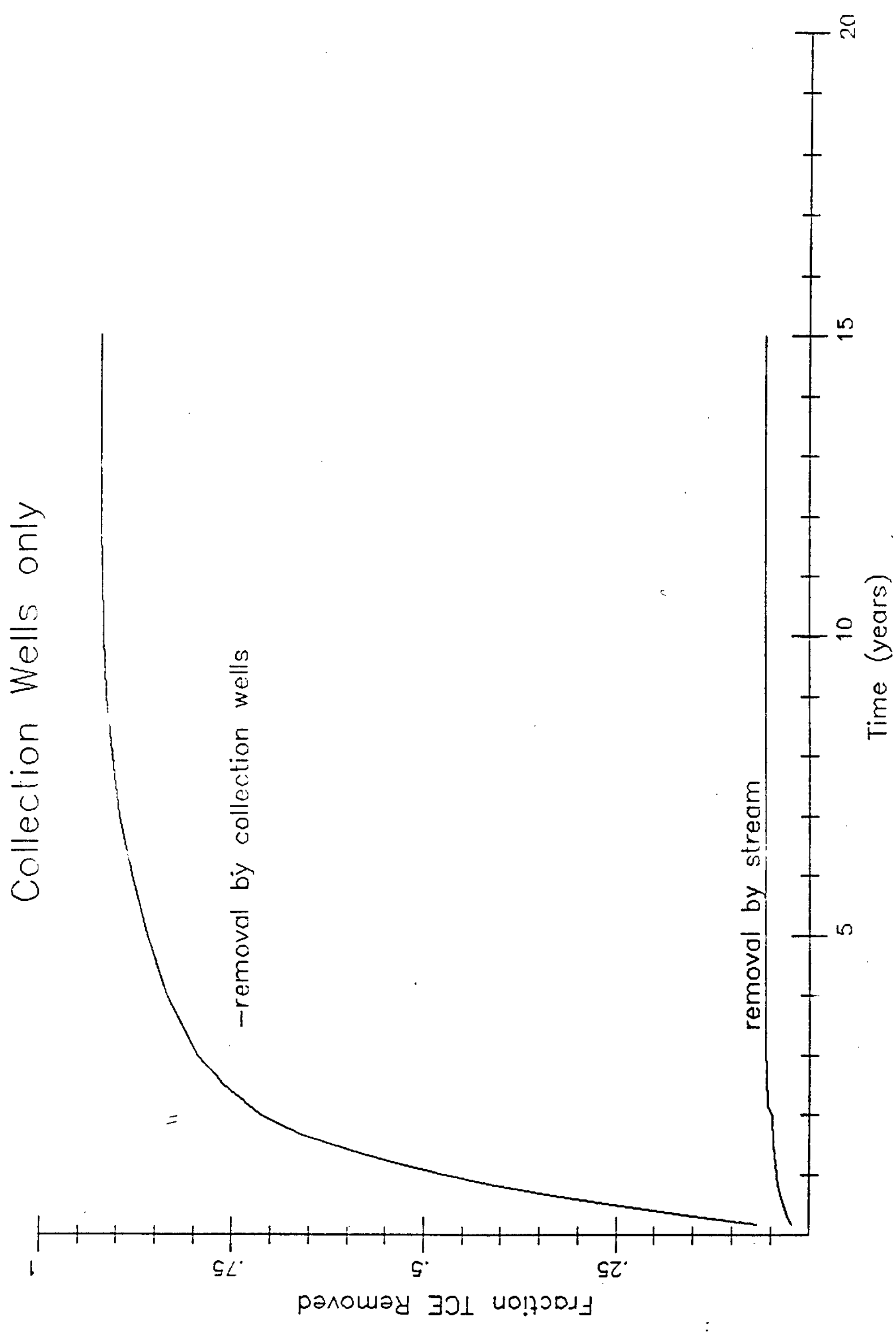

Figure III-18

Figure III-19 shows the TCE concentrations in the pumpage for each of the wells. Well 2 has the highest concentrations since it is in the middle of the plume. Well 3 also intersects the edge of the plume. Well 1 collects very little contamination, but it is an important and necessary component of the hydraulic barrier. Figure III-20 shows the composite concentration of TCE that will be treated. One hundred and eight gpm will be pumped and piped to a treatment facility, probably an air stripper. Initially, concentrations of TCE in the pumpage will be high, approximately 500 ppb. TCE concentrations will decline rapidly over time and probably be less than 100 ppb at the end of three years. At the end of ten years concentrations are less than 5 ppb.

Figure III-21 shows TCE concentrations in the seepage to Green Pond Brook over time. The initial concentrations are approximately 90 ppb. TCE concentrations in stream seepage decline rapidly; at the end of a year they are less than 10 ppb. A small amount of TCE still reaches the stream over time. The blip in the graph at two years is a slug of TCE reaching the stream after the simulation reaches steady state. Part of the initial plume between the collection wells and the stream is right at the limit of well influence (the stagnation point). As well pumping continues, this part of the plume continues to be at the stagnation point. Finally, steady state is reached, and the particles representing the plume either travel to the stream or the well. Assuming an average flow for Green Spring Brook of about six cfs, the maximum instream concentration of TCE would be 4.8 ppb.

The collector wells provide a good barrier to contaminant transport in the water table aquifer. They are also effective in removing the TCE from the aquifer.

d. Recharge Well scenario

One way of speeding up a ground water cleanup with collection wells is to inject the treated water upgradient of the plume. This allows the velocity of ground water flow towards the collector wells to be increased. A scenario was designed to have injection wells on the upgradient side of building 24 to reinject the treated ground water into the water table aquifer.

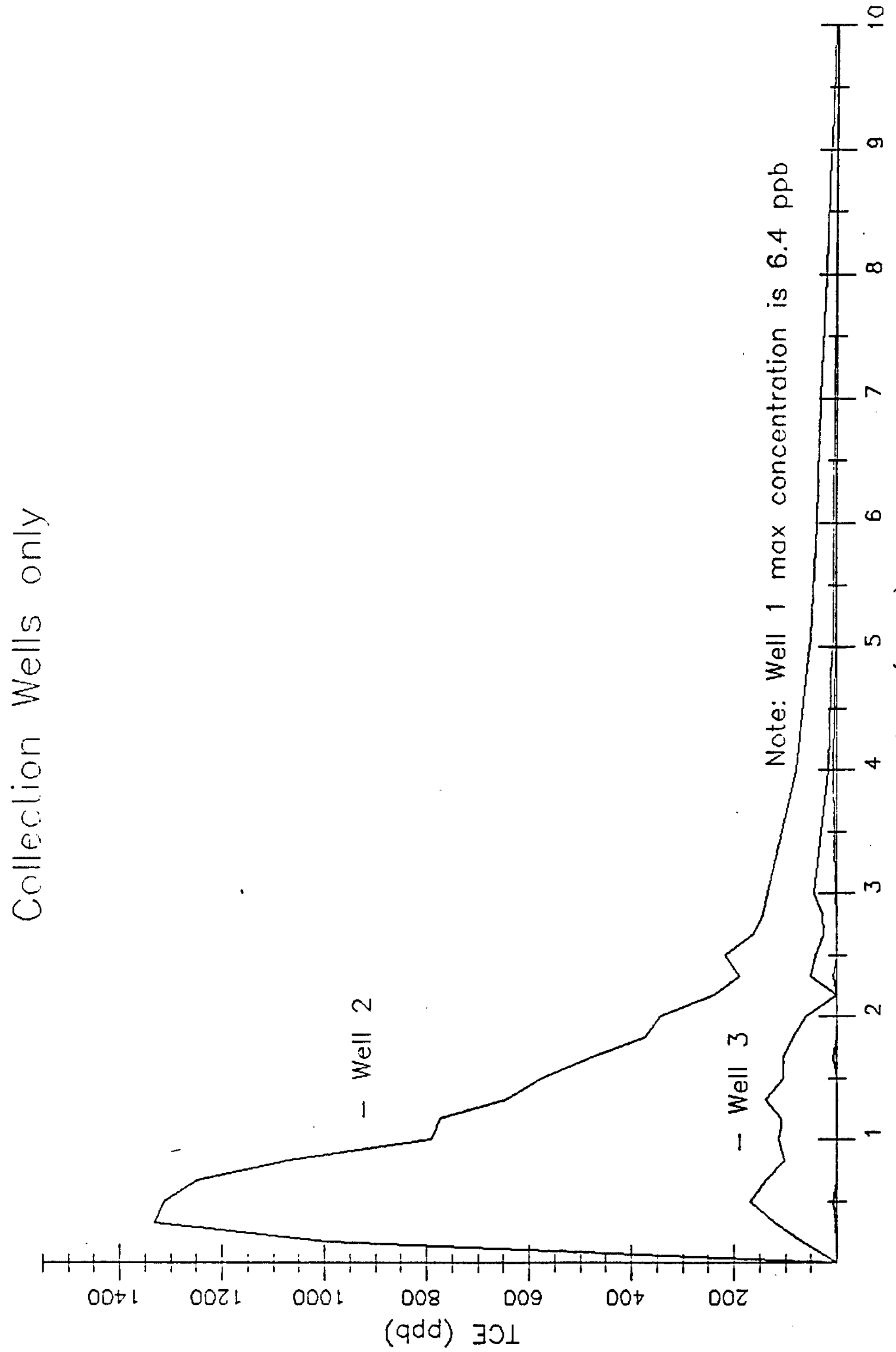

Figure III-19

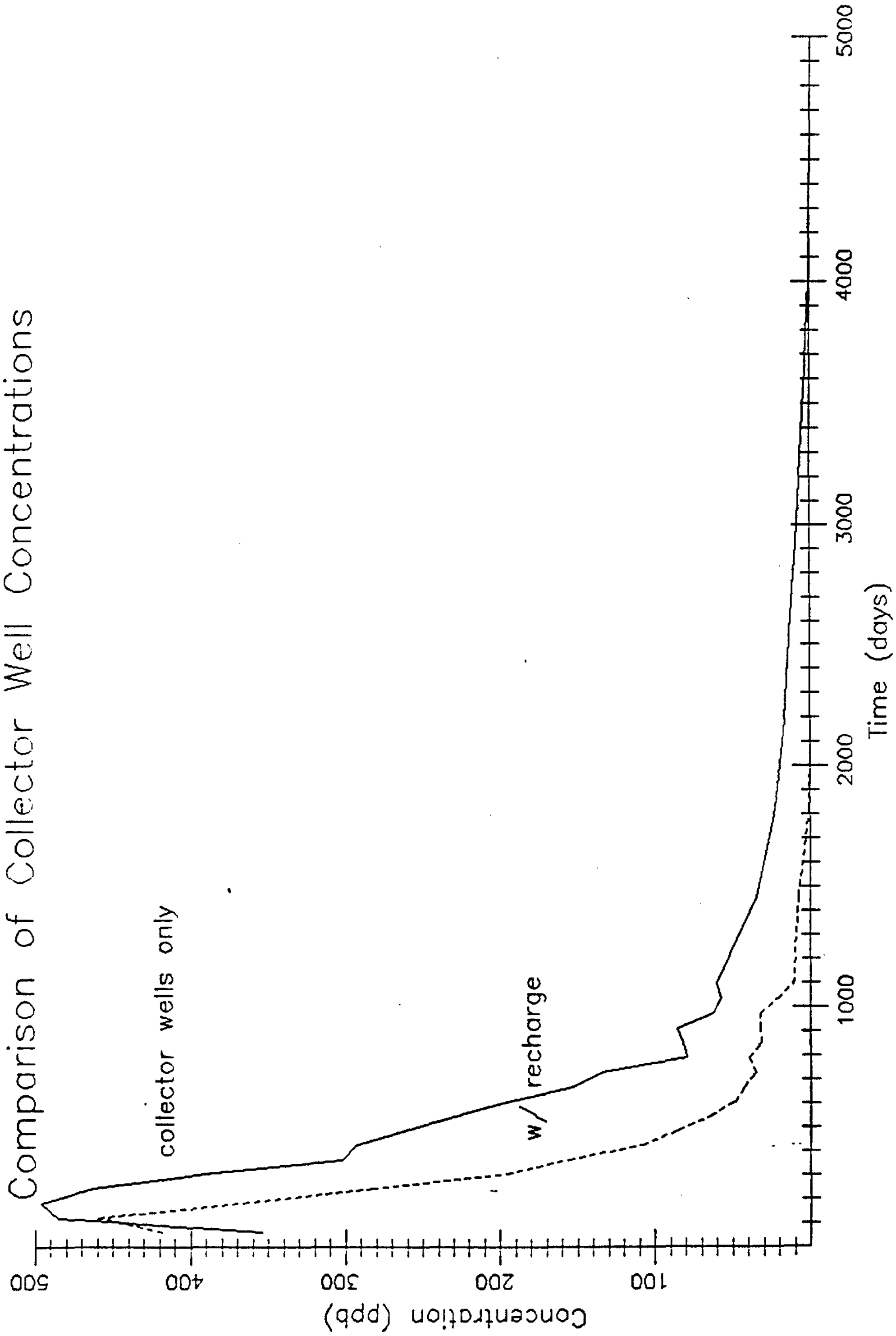

Figure III-20

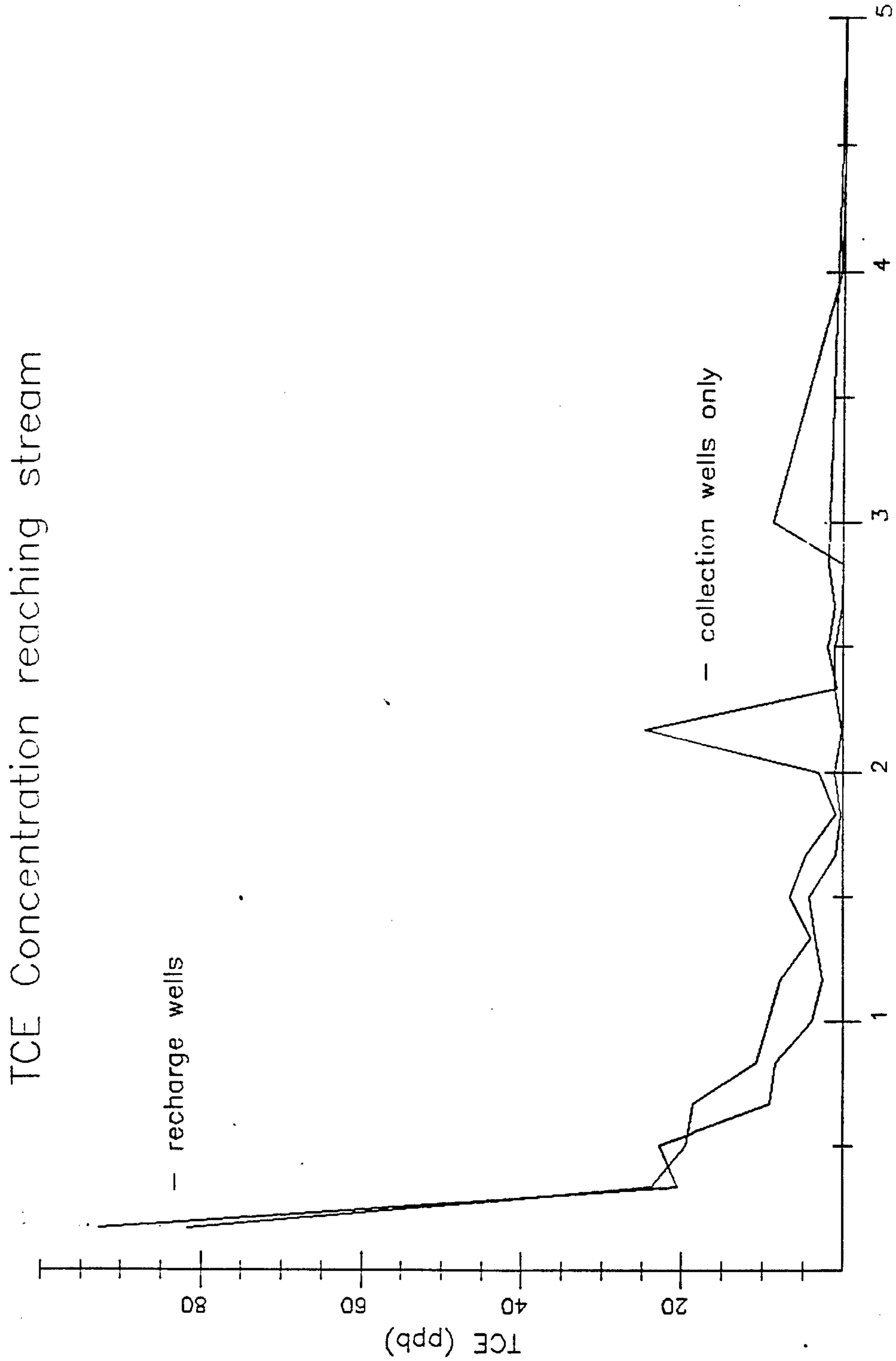

Figure III-21

One constraint on this alternative was the amount of buildup that could occur in the injection wells before water bubbled out of the ground. Injection wells typically have clogging problems due to bacterial and chemical changes in the treated water, so well losses may be significant. To minimize these problems, the flow was split among the four injection well sites along Bear Swamp Brook. The first well was along 2nd Avenue north of Building 60. The second well was north of Building 24, east of 4th Street. The third well was north of Building 24, approximately 240 feet west of the second well. The fourth well was west of Farley Ave immediately adjacent to Bear Swamp Brook.

Collector well locations were the same as in the previously described collector well only scenario. Injection of treated ground water permits higher pumping rates to be used. Each of the collector wells were assumed to be pumped at a rate of 72 gpm, twice that used in the collector well scenario. Of the total of 216 gpm that will be treated, 200 gpm would be injected back into the water table aquifer. By letting some of treated water discharge to surface water insures that the system as a whole (total of pumping and injection) causes a slight depression in the water table, so if the assumptions are incorrect, contamination will still remain in the area, rather than being pushed away faster than it normally would. Each injector well would recharge 50 gpm.

Recharge (injection) wells typically have clogging problems due to chemical and/or biological reactions. The well loss routine of the modified MODFLOW model was used to represent potential clogging problems. Each injection well was assumed to be approximately 80 percent efficient at the design recharge rate of 50 gpm. The well loss was assumed to follow an equation of the following form.

$$\text{well loss} = A\,Q^2$$

where

well loss = additional head loss caused by well inefficiency (ft)
A = coefficient (day^2/ft^5)
Q = discharge rate (ft^3/day)

The coefficient (A) was calculated to be 4.6E-8. This coefficient was used at each injection well.

The MODFLOW model was used to simulate the ground water flow impacts of the collector and recharge wells. Figure III-22 shows the well locations. The following well locations were used.

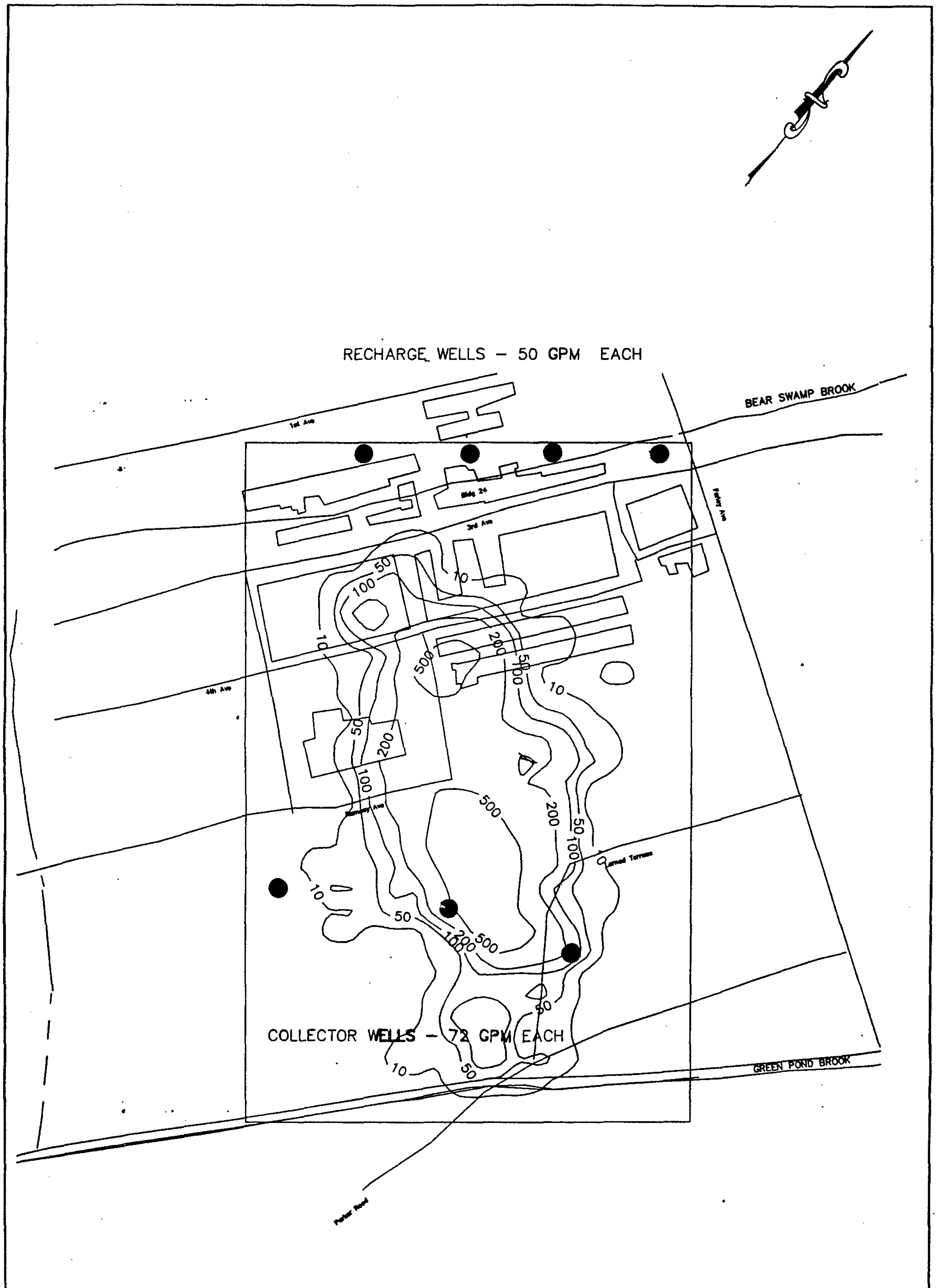

Figure III-22

DESIGNED DHK 2/89 DATE		ENGINEERING TECHNOLOGIES ASSOCIATES, INC.	PICATINNY ARSENAL, N.J. GROUND WATER MODELING
DRAWN PPM 2/89 DATE		ENGINEERS • PLANNERS • SURVEYORS	COLLECTION WELL AND RECHARGE SCENARIO
CHECKED ______ DATE		3458 ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	TCE CONCENTRATIONS (ppb) – YEAR 1
APPROVED ______ DATE			SCALE 1"=250 CONTRACT NO: 8313.10 DATE 3/1/89 SHEET

Well		Column	Row	Pumping Rate (ft^3/day)
Collector	1	9	27	13861
Collector	2	17	28	13861
Collector	3	23	30	13861
Recharge	1	13	7	-9626
Recharge	2	18	7	-9626
Recharge	3	22	7	-9626
Recharge	4	27	7	-9626

Each well was assumed to have a radius of 0.25 feet and fully penetrate the water table aquifer. The collector wells were assumed to be 100 percent efficient (no well loss). The recharge wells had the well loss coefficients previously described. The flow model was run for five years with 60.833 day time steps. Steady state was reached at about two years. Figure III-23 shows the steady state position of the water table. Steady state well drawdowns and buildups are

Well		Drawdown (ft)
Collector	1	27.3
Collector	2	28.6
Collector	3	28.0
Recharge	1	-18.5
Recharge	2	-19.2
Recharge	3	-18.9
Recharge	4	-18.2

The buildups calculated for the recharge wells are greater than the depth to ground water so gravity pressure would not be adequate for the injection wells. Water would have to be forced into the ground under pressure. This also may cause ground water to reemerge from the ground near the well. The simulation indicates that 14 gpm of the injected water comes out in Bear Swamp Brook, which increases the flow of Bear Swamp Brock by about seven percent. The collector wells cause less ground water to flow into Green Pond Brook. Stream depletion by the wells at steady state is 56 gpm, 2.2 percent of stream flow.

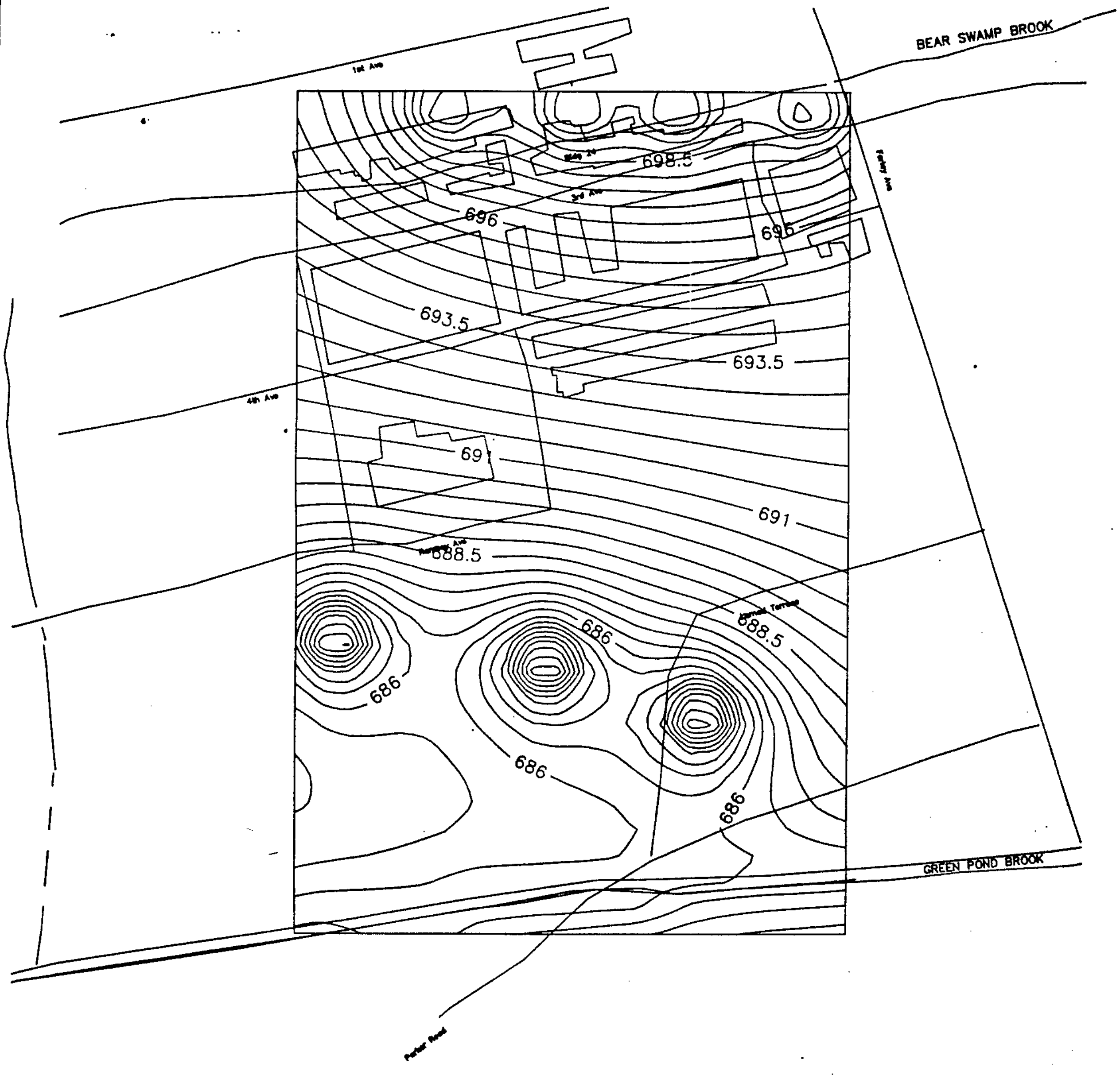

Figure III-23

DESIGNED DHK 2/89 DRAWN PPM 2/89 CHECKED APPROVED	ENGINEERING TECHNOLOGIES ASSOCIATES, INC. ENGINEERS • PLANNERS • SURVEYORS 3458 ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	PICATINNY ARSENAL, N.J. GROUND WATER MODELING COLLECTION WELL AND RECHARGE SCENARIO STEADY STATE WATER TABLE SCALE: 1"=250 CONTRACT NO.: 8313.10 DATE: 3/1/89 SHEET:

PREMOD3D was used to generate velocity files at intervals of 60.833 days. The resulting velocity files were input to RAND3D. For this initial remedial action scenario simulation a smaller number of particles and a larger particle weight were used. The particle weight was 0.08316 lbs. Forty-five hundred particles were used initially in the water table aquifer. No particles were started in the confined glacial aquifer. All other solute transport parameters were as discussed previously. The model was run for ten years. Times steps of 60.833 days were used for the first three years to simulate a transient flow field. The remaining time steps were one year in length.

Figure III-24 shows the rate of TCE removal from the aquifer by the wells and the stream. After three years of pumping, 96 percent of the TCE has been removed from the aquifer, with 92 percent being removed by the collection wells and four percent entering Green Pond Brook. After six years of pumping, 98 percent of the TCE has been removed. At this point, the water table aquifer is free of contamination. TCE is still moving through the confining layer into the confined glacial aquifer at this time. The contamination moves rapidly through the confined glacial aquifer and begins to travel up through the confining layer under the collection wells. Travel through the confining layer is relatively slow, although the recharge wells cause vertical gradients through the confining layer to be larger, and contaminant movement faster than in the collection well only scenario. At the end of ten years of simulation, approximately two percent of the initial contamination is still in the aquifer system.

Figure III-25 shows the TCE concentrations in the pumpage for each of the wells. Well 2 has the highest concentrations since it is in the middle of the plume. Well 3 also intersects the edge of the plume. Well 1 collects very little contamination, but it is an important and necessary component of the hydraulic barrier. Figure III-20 shows the composite concentration of TCE that will be treated. Two hundred and sixteen gpm will be pumped and piped to a treatment facility, probably an air stripper. Initially, concentrations of TCE in the pumpage will be high, approximately 450 ppb. TCE concentrations will decline rapidly over time and probably be less than 100 ppb at the end of two years. At the end of five years concentrations are less than 5 ppb.

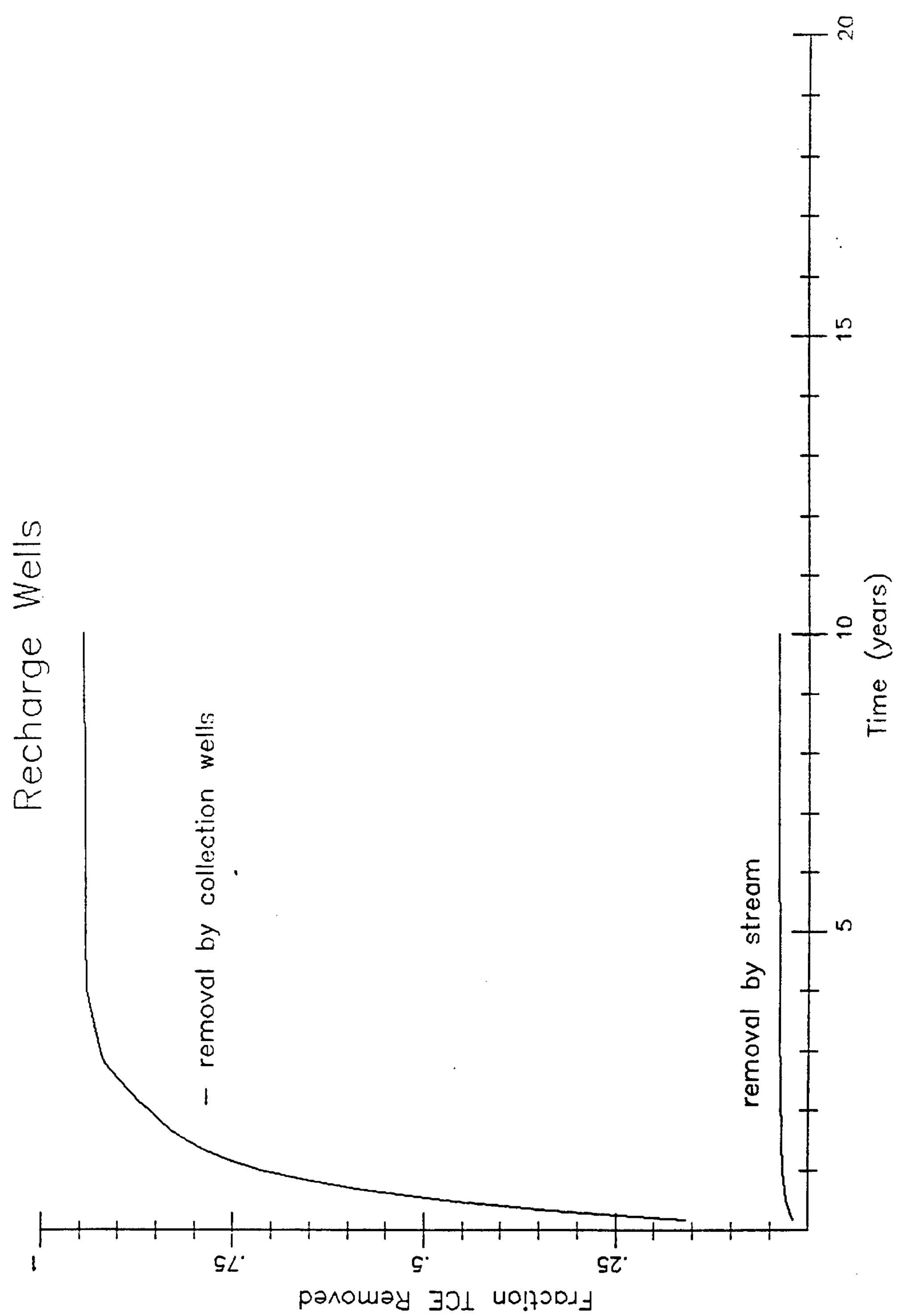

Figure III-24

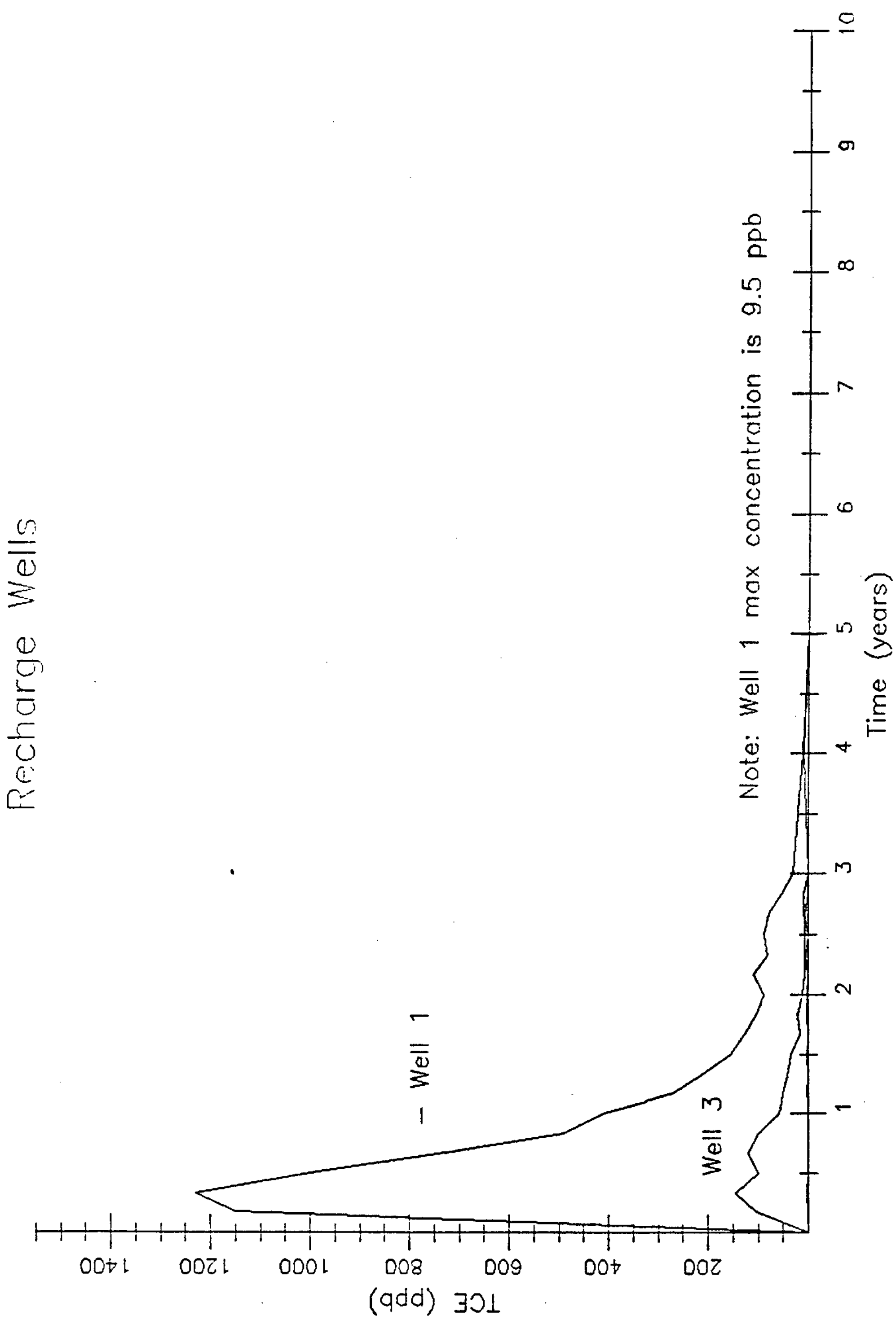

Figure III-25

Figure III-21 shows TCE concentrations in the seepage to Green Pond Brook over time. The initial concentrations are approximately 90 ppb. TCE concentrations in stream seepage decline rapidly; at the end of a year they are less than 10 ppb. A small amount of TCE still reaches the stream over time. Assuming an average flow for Green Spring Brook of about six cfs, the maximum instream concentration of TCE would be 4.8 ppb.

The use of recharge wells to push the TCE plume towards the collection wells theoretically offers the fastest cleanup of the ground water at the site. This scenario may be infeasible, however; since it may not be possible to inject treated water into the aquifer at the proposed rates. Significant amounts of water may surface and/or discharge to Bear Swamp Brook. The added cost and maintenance of the injection wells would also be significant. A pilot study of the chemical capability of the treated water with the existing ground water is necessary to see if the treated water could be injected without causing chemical precipitation to occur.

e. Collector wells with discharge to Bear Swamp Brook

After the three alternative scenarios described above were simulated and discussed, three additional scenarios were considered. One of these was the initial collector well scenario with discharge of the treated water to Bear Swamp Brook. Bear Swamp Brook is normally a losing (influent) stream. By increasing the flow in the stream, additional water would recharge into the water table aquifer on the upgradient side of Building 24. This scenario would provide the similar benefit as the recharge well scenario without the expense or problems of recharge wells.

All of the flow model inputs to this scenario were identical to the inputs described for the initial collector well scenario with the exception of the head in Bear Swamp Brook. The treated pumpage of 108 gpm (0.24 cfs) would be discharged to Bear Swamp Brook at Farley Avenue. The existing flow of Bear Swamp Brook was assumed to be 0.42 cfs. This discharge was computed in the seepage analysis for Bear Swamp Brook (Sargent et al, 1988). Using Manning's equation, a slope of 0.0034, a rectangular channel width of six feet, and a roughness coefficient (n) of 0.03, the increase in depth will be about 27 percent.

An arbitrary stream depth of 1.0 feet was used for Bear Swamp Brook in the calibration of the flow model. The depth was increased to 1.27 feet, and the flow model run with the collector wells. Figure III-26 shows the steady state water table. Steady state well drawdowns are:

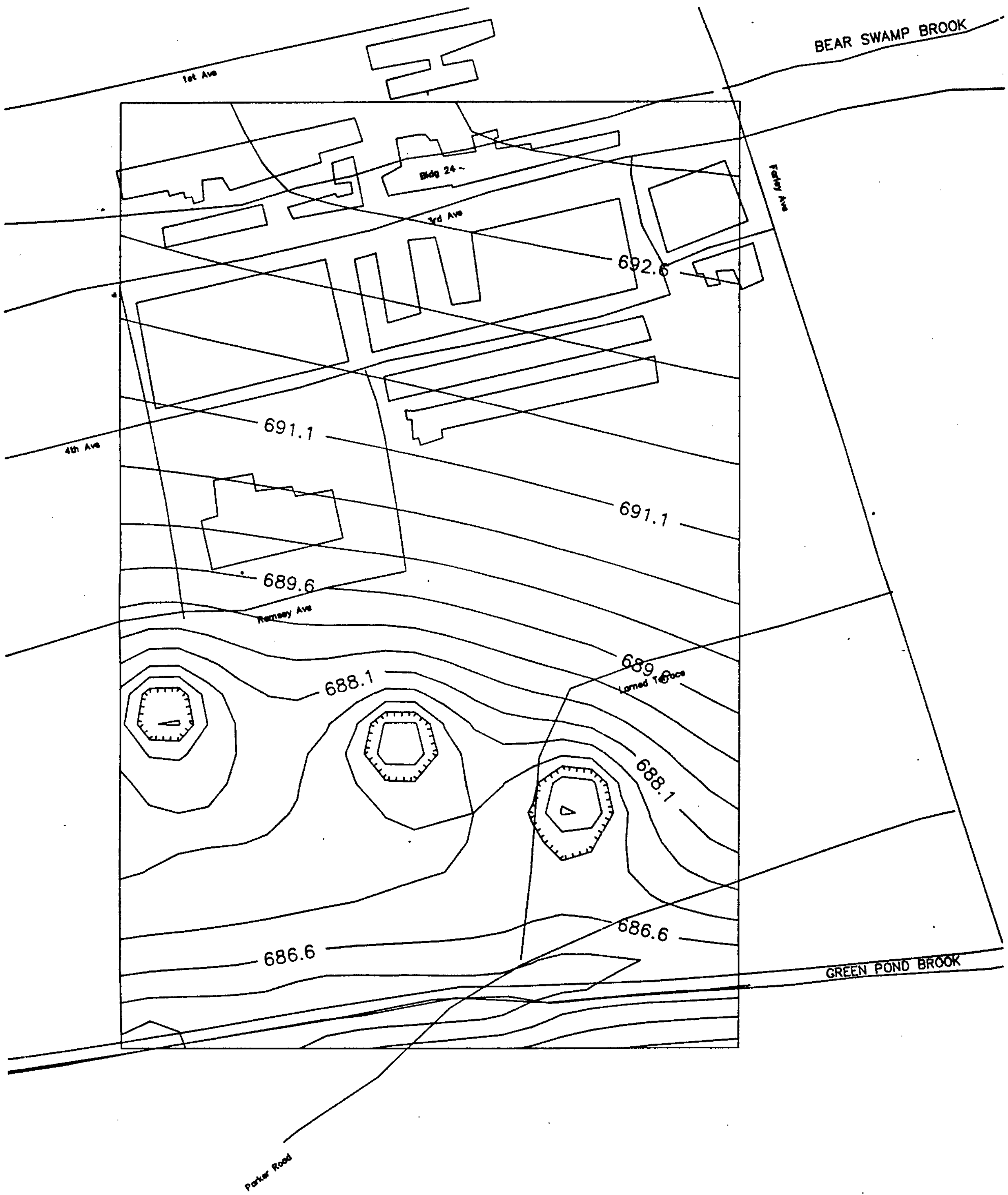

Figure III-26

WATER TABLE AQUIFER

DESIGNED DHK 2/89	ENGINEERING TECHNOLOGIES ASSOCIATES, INC.	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING
DRAWN PPM 2/89	ENGINEERS • PLANNERS • SURVEYORS	COLLECTION WELL SCENARIO & DISCHARGE TO BEAR SWAMP BROOK
CHECKED	3458 ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	STEADY STATE WATER TABLE
APPROVED		SCALE 1"=200' CONTRACT NO. 8313.10 DATE 3/14/89 SHEET

Well	Drawdown (ft)
1	12.2
2	12.7
3	12.4

These results are almost identical to those of the initial collector well scenario. Stream depletion was almost identical to that calculated in the initial collector well scenario.

PREMOD3D was used to generate velocity files at intervals of 60.833 days. The resulting velocity files were input to RAND3D. The solute transport parameters were as discussed previously. Particles were started in both the water table aquifer and the confined glacial aqiufer (9573 particles with a weight of 0.04314 lbs each). The model was run for twenty years. Times steps of 60.833 days were used for the first three years to simulate a transient flow field. The remaining time steps were one year in length up to fifteen years, followed by a five year step.
Figure III-27 shows the rate of TCE removal from the aquifers by the wells and the stream. After three years of pumping, 84 percent of the TCE has been removed from the aquifer, with 80 percent being removed by the collection wells and four percent entering Green Pond Brook. After six years of pumping, 93 percent of the TCE has been removed, with 89 percent being removed by the collection wells, and four percent entering Green Pond Brook. The differences between this scenario and the initial collection well scenario are believed to be due mostly to the differences in initial pollutant distribution. After six years, the water table aquifer is almost free of contamination. There is still some TCE in the confining layers and the increased recharge to the water table along Bear Swamp Brook causes the TCE that started at Building 24 to move north away from the stream. At the end of twenty years of simulation, approximately three percent of the initial contamination is still in the aquifer system.

Figure III-28 shows the TCE concentrations in the pumpage for each of the wells. Well 2 has the highest concentrations since it is in the middle of the plume. Well 3 also intersects the edge of the plume. Well 1 collects very little contamination, but it is an important and necessary component of the hydraulic barrier which the wells form. Figure III-29 shows the composite concentration of TCE that will be treated. One hundred and eight gpm will be pumped and piped to a treatment facility, probably an air stripper. Initially, concentrations of TCE in the pumpage will be high, approximately 500 ppb. TCE concentrations will decline rapidly over time and probably be less than 100

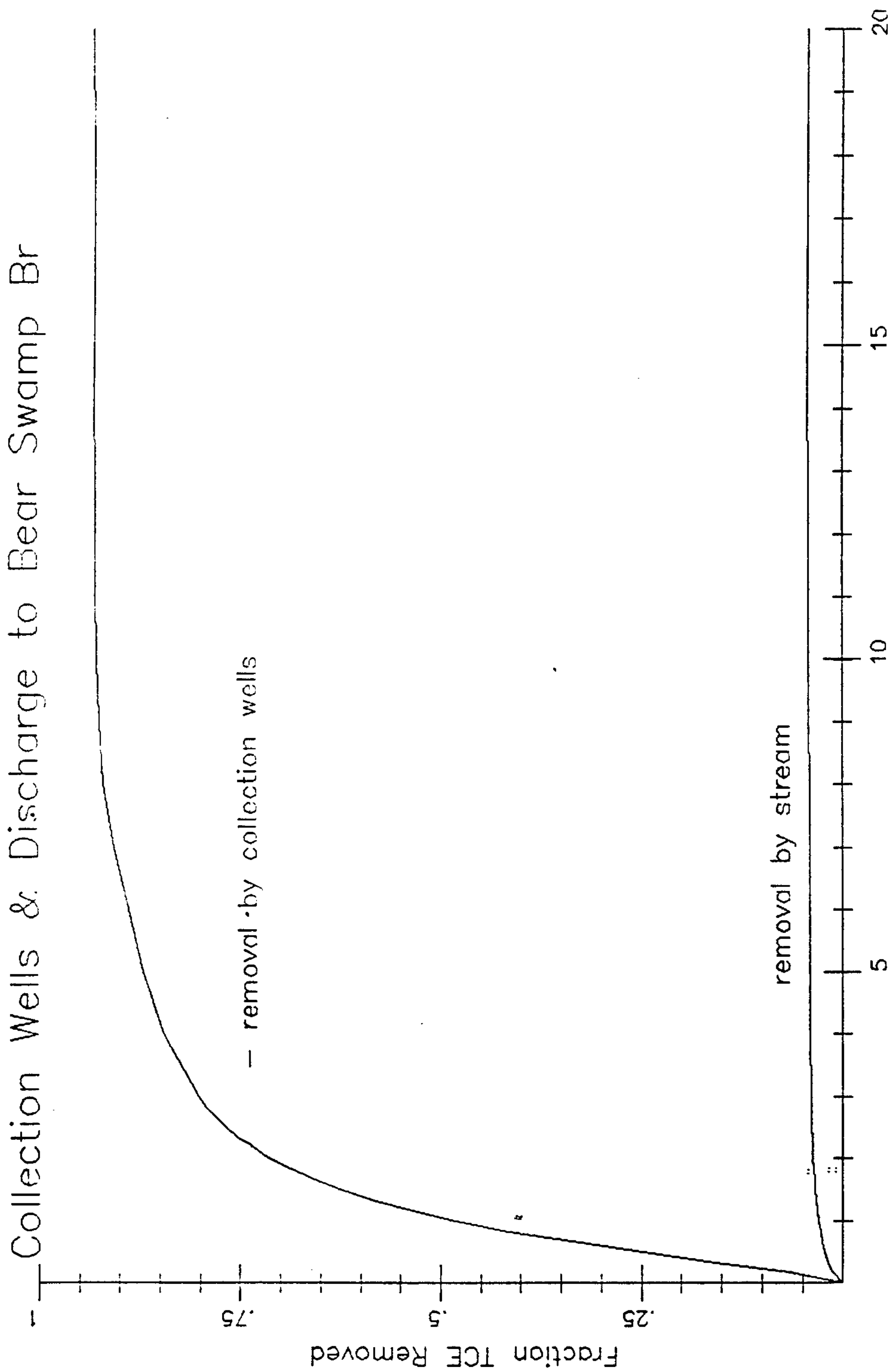

Figure III-27

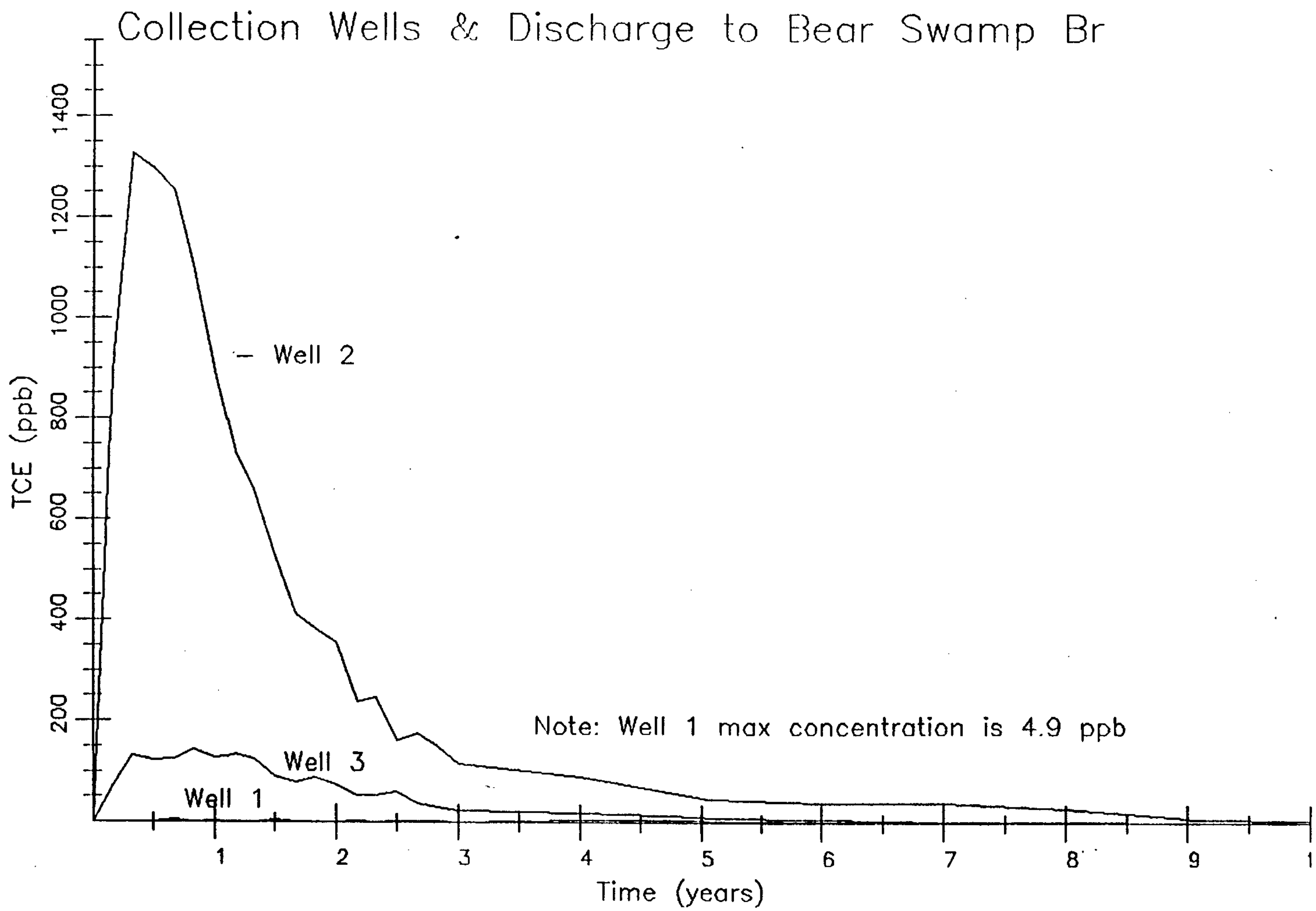

Figure III-28

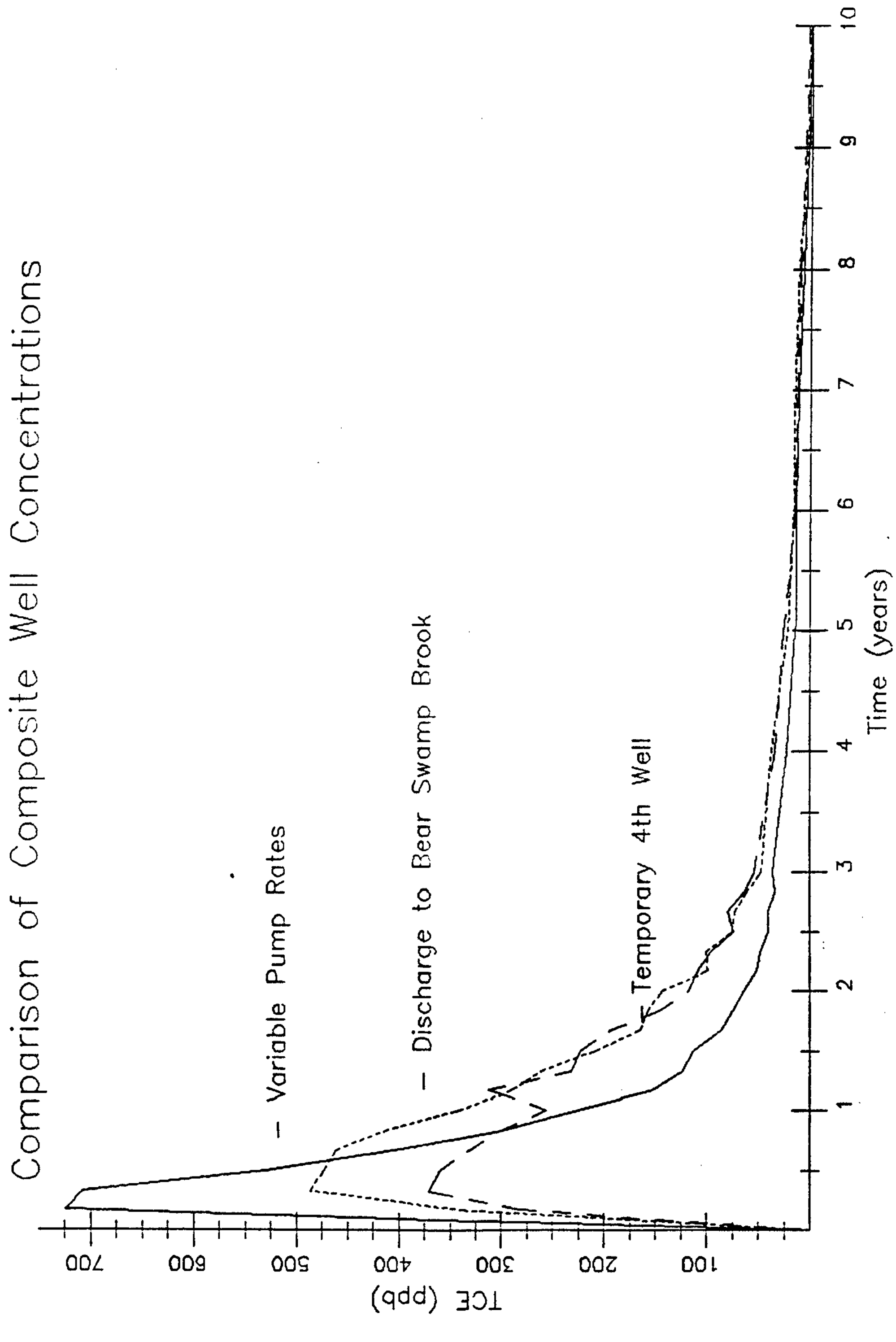

Figure III-29

ppb at the end of three years. At the end of ten years concentrations are less than 5 ppb.

Figure III-30 shows TCE concentrations in the seepage to Green Pond Brook over time. The initial concentrations are approximately 40 ppb. TCE concentrations in stream seepage decline rapidly; at the end of a year they are about 10 ppb. Some small amount of TCE still reaches the stream over time. The unevenness in the graph is due to the random nature of the model; relatively few particles reach the stream, thus the random nature of the dispersion algorithm causes the predicted concentrations to fluctuate in time. Assuming an average flow for Green Spring Brook of about six cfs, the maximum instream concentration of TCE would be 2 ppb.

Discharging the treated water to Bear Swamp Brook behind Building 24 has relatively little impact on the efficiency of the initial collection well scenario. If there is any contamination on the upgradient side of Bear Swamp Brook, this alternative may be a poor one. The increased head in Bear Swamp Brook alters the direction of flow on the upgradient side of the brook to be northwest rather than southwest as it is under all the other scenarios. The discharge to Bear Swamp Brook may cause contamination to move away from the site and the collector wells. One would not expect TCE to have been spilled on the upgradient side of Bear Swamp Brook, but lagoon overflows or some other source of TCE may have caused this to happen.

To improve the efficiency of this alternative, one would have to decrease the resistance of the bottom of Bear Swamp Brook to infiltration. It may be possible to install an infiltration trench in the bottom of the brook to permit rapid infiltration of water. This alternative would require the same type of chemical study that would be required for the recharge well alternative. It would also require that there be a sediment pond upstream of the trench to prevent sediment from clogging the trench.

f. Collector wells with temporary fourth well

One of the problems with the initial collector well scenario was the fairly substantial amount (12 lbs) of TCE that enters Green Pond Brook during the first year of the simulation. TCE between the stream and collection wells will move to the stream until the wells establish their zone of influence. Placing a fourth well immediately adjacent to Green Pond Brook and pumping it during the early stages of the remedial action was suggested as a method of preventing almost any TCE from entering the stream.

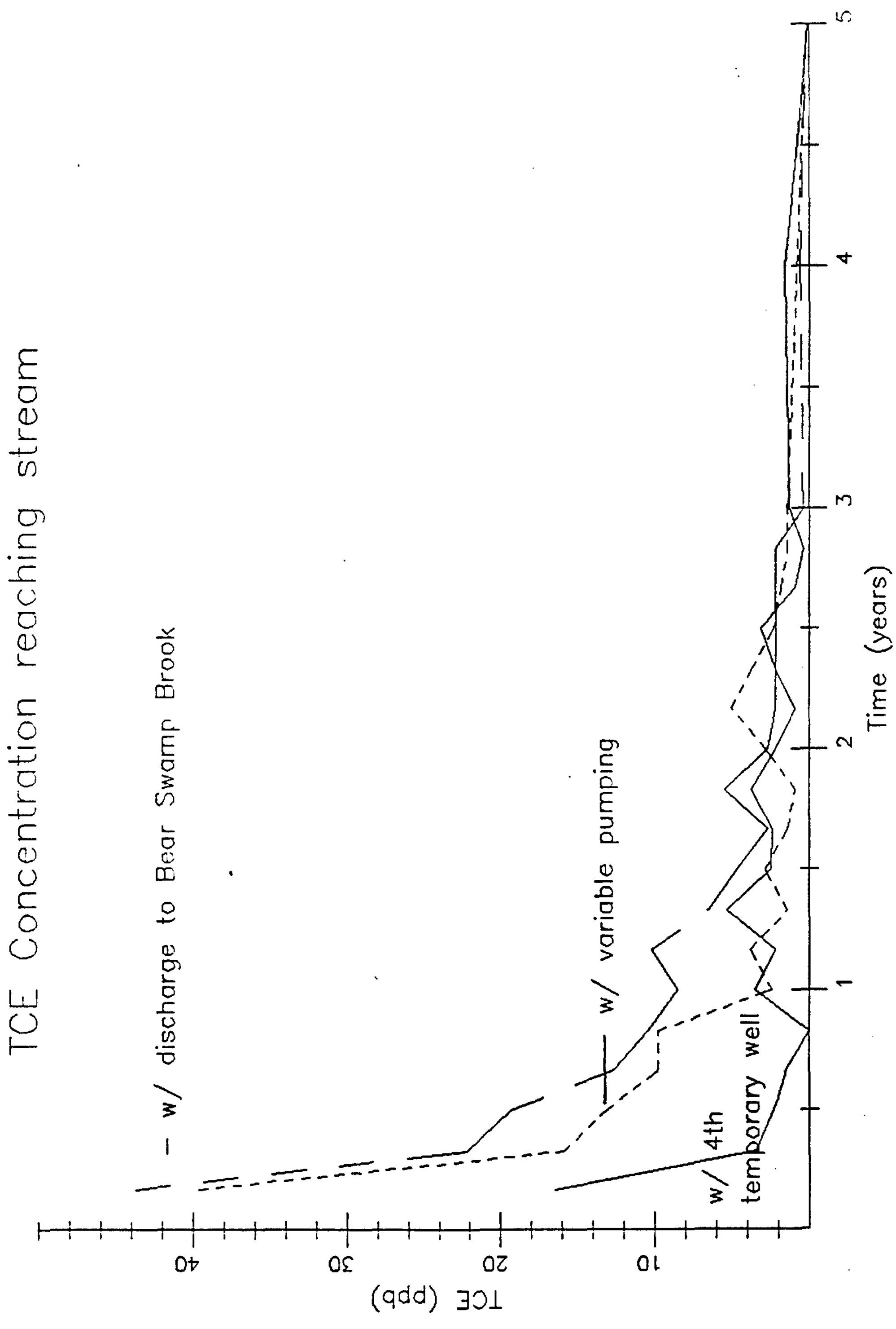

Figure III-30

The position and pumping rate of this temporary well was selected by calculating with analytical formulas, the pumpage necessary to capture the full width of the TCE plume at Green Pond Brook in one year of pumping. The TCE plume was assumed to be 500 feet wide at the stream. The collection radius of a pumping well in a uniform, homogeneous aquifer with no dispersion is given by the following equation:

$$r^2 = Qt/\pi bn$$

where

r = capture radius
Q = constant pumping rate
t = time of pumping
b = thickness of aquifer
n = porosity

Assuming a capture radius of 250 feet, an aquifer thickness of 40 feet, and a porosity of 0.2, a pumping rate of 22 gpm is required to capture all of the plume within one year. This pumping rate was doubled to account for leakage, dispersion, and additional TCE.

The fourth well would be placed east of Larned Terrace along Green Pond Brook. Figure III-31 shows the location of the four wells during the first year. This fourth well would be pumped at a rate of 44 gpm for one year. All other inputs to the flow model were the same as they were for the initial collection well scenario. The following well locations were used:

Well	Column	Row	Pumping Rate (ft^3/day)	
1	9	27	6930	
2	17	28	6930	
3	23	30	6930	
4	21	35	8470	- only for first year

Each collector well was assumed to have a radius of 0.25 feet and fully penetrate the water table aquifer. The wells were assumed to be 100 percent efficient (no well loss). The flow model was run for five years with 60.833 day time steps. Steady state was reached at about two years. The steady state water table is identical to that of the initial collector well scenario as well as drawdowns in the three collector wells (see Figure III-17). Drawdown in the temporary fourth well at the end of one year of pumping is 14.3 feet. The water table level at end of one year is shown in Figure III-32. Stream depletion by the wells at steady state is 45 gpm, 1.8 percent of stream flow. Stream depletion at the end of the first year, which includes the

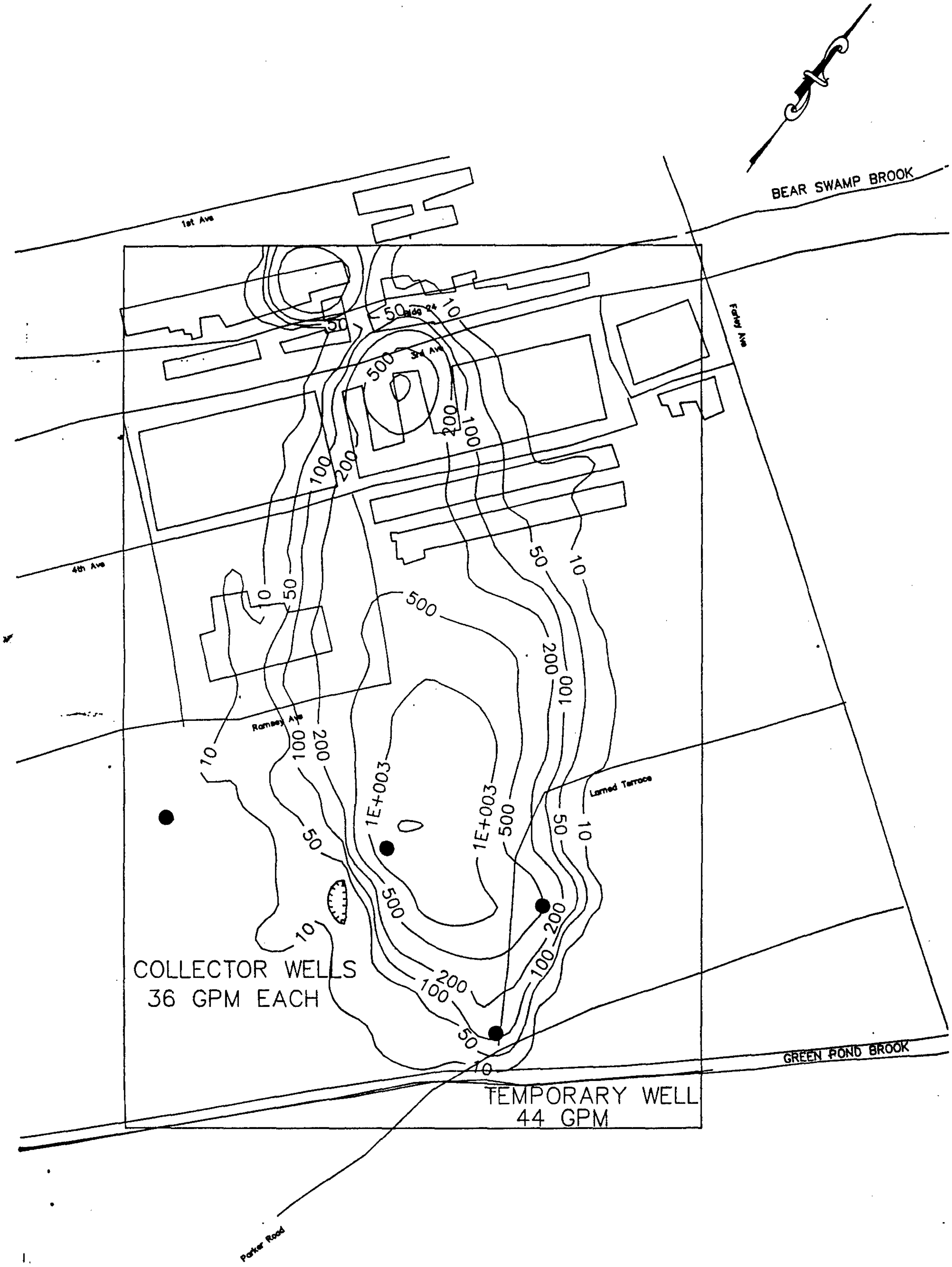

Figure III-31

WATER TABLE AQUIFER

DESIGNED	DHK	2/89	DATE
DRAWN	PPM	2/89	DATE
CHECKED			DATE
APPROVED			DATE

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PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

COLLECTION WELL SCENARIO
with TEMPORARY FOURTH WELL
TCE CONCENTRATIONS (ppb) – YEAR 1

SCALE: 1"=200' CONTRACT NO: 8313.10 DATE: 3/8/89 SHEET:

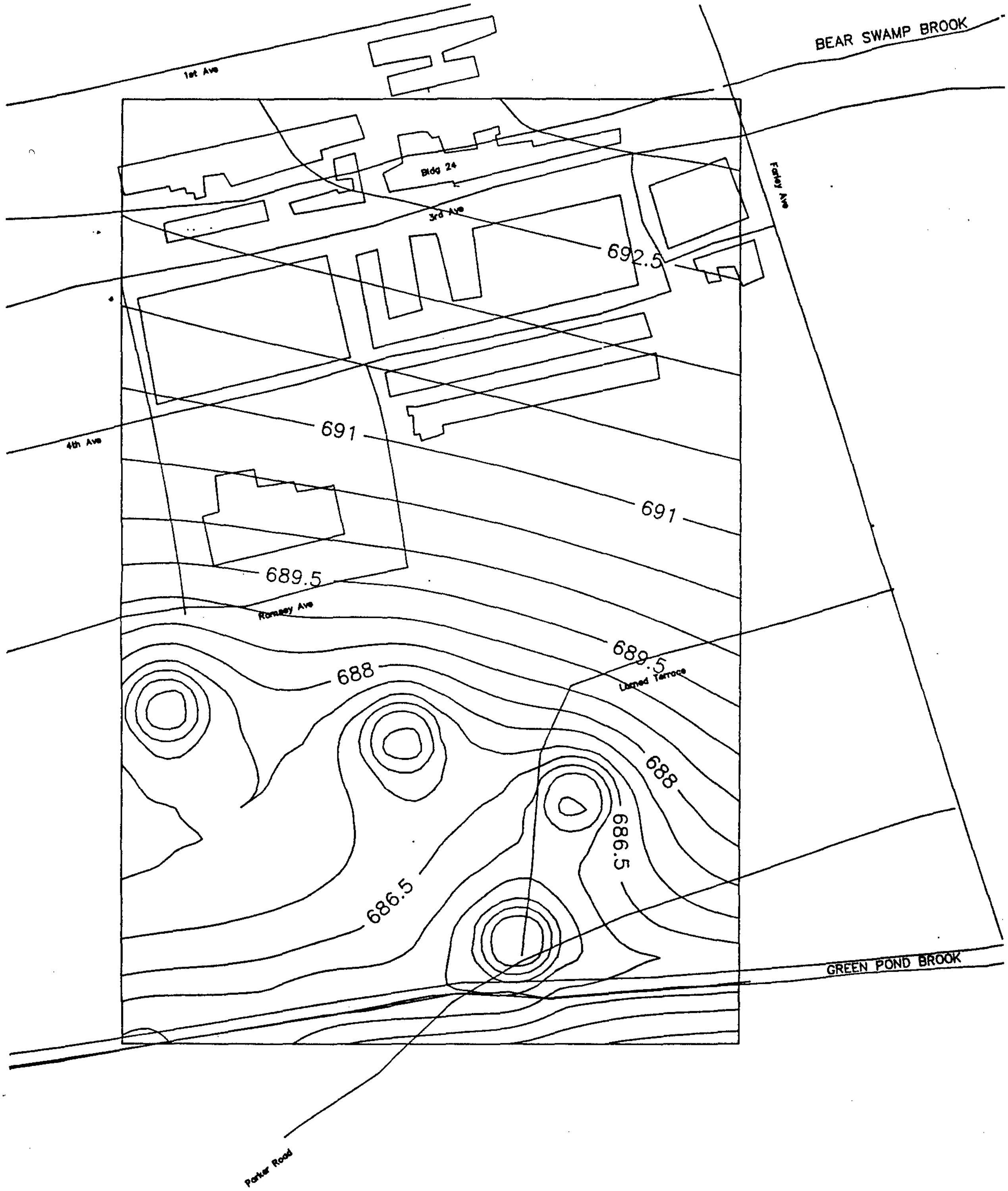

Figure III-32

DESIGNED	DHK 2/89
DRAWN	PPM 2/89
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APPROVED	

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PICATINNY ARSENAL, N.J. GROUNDWATER MODELING
COLLECTION WELL SCENARIO
WATER TABLE — YEAR 1

SCALE 1"=200' | CONTRACT NO. 8313.10 | DATE 3/8/89 | SHEET

rather large depletion caused by the temporary fourth well, is 63 gpm (0.14 cfs).

PREMOD3D was used to generate velocity files at intervals of 60.833 days. The resulting velocity files were input to RAND3D. The solute transport parameters were as discussed previously (9573 particles with a weight of 0.04314 lbs each). The model was run for twelve years. Time steps of 60.833 days were used for the first three years to simulate a transient flow field. The remaining time steps were one year in length.

Figure III-33 shows the rate of TCE removal from the aquifer by the wells and the stream. After three years of pumping, 85 percent of the TCE has been removed from the aquifer, with 84 percent being removed by the collection wells and one percent entering Green Pond Brook. After six years of pumping, 94 percent of the TCE has been removed, with 92 percent being removed by the wells and 2 percent entering the stream. At this point, the water table aquifer is almost free of contamination, but some TCE is still moving through the confining layer into the confined glacial aquifer. At the end of twelve years of simulation, approximately three percent of the initial contamination is still in the aquifer system.

Figure III-34 shows the TCE concentrations in the pumpage for each of the wells. Well 2 has the highest concentrations since it is in the middle of the plume. Well 3 also intersects the edge of the plume. Well 1 collects very little contamination, but it is an important and necessary component of the hydraulic barrier which the wells form. Well 4 has a relatively small TCE concentration because of the significant amount of water pumped from Green Pond Brook. Figure III-29 shows the composite concentration of TCE that will be treated. One hundred and fifty-two gpm will be pumped for the first year and piped to the treatment facility, probably an air stripper. One hundred and eight gpm will be pumped in succeeding years. Initially, concentrations of TCE in the pumpage will be high, approximately 350 ppb. TCE concentrations will decline rapidly over time and probably be less than 100 ppb at the end of three years. At the end of ten years concentrations are less than 5 ppb.

Figure III-30 shows TCE concentrations in the seepage to Green Pond Brook over time. The initial concentrations are approximately 20 ppb. TCE concentrations in stream seepage decline rapidly; at the end of a year they are less than 10 ppb. The unevenness in the graph is due to the random nature of the model; relatively few particles reach the stream, thus the random nature of the dispersion algorithm causes the predicted concentrations to fluctuate in time. Assuming an average flow for Green Spring Brook

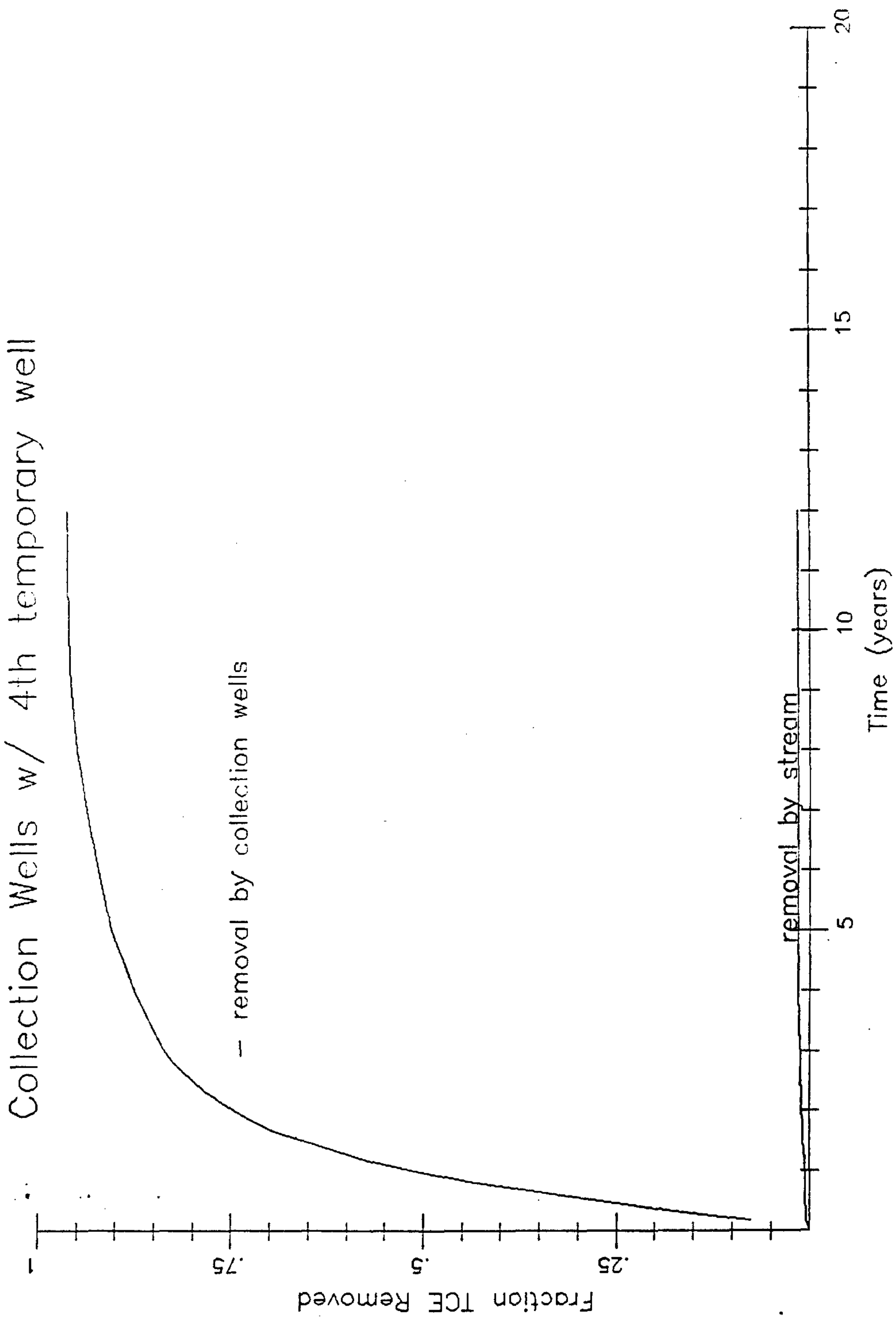

Figure III-33

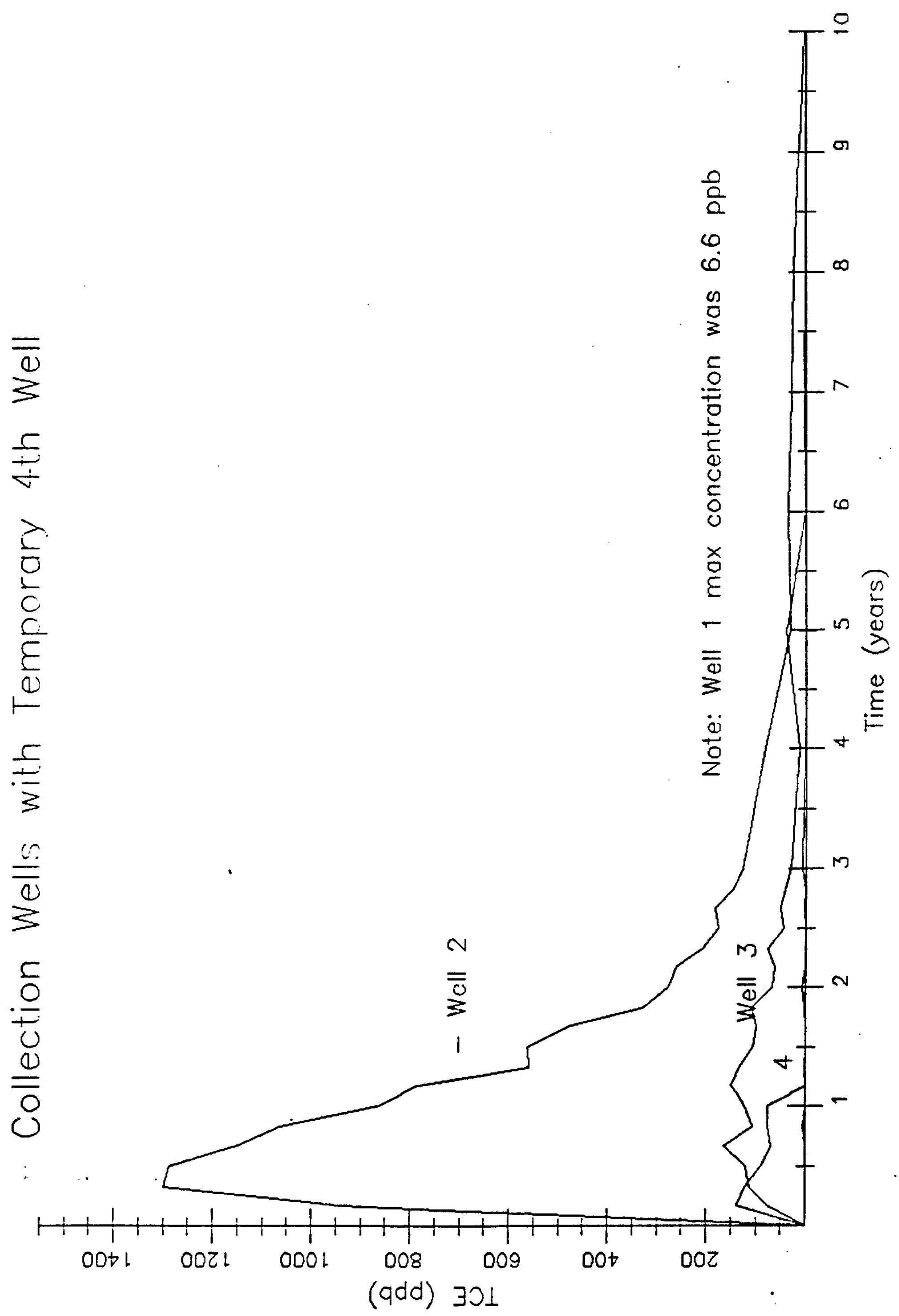

Figure III-34

of about six cfs, the maximum instream concentration of TCE would be about 1 ppb. The temporary fourth well does prevent a significant amount of TCE from reaching Green Pond Brook when compared with the other alternatives. It results in more clean water being pumped and treated for the first year, however. The concentration of TCE in the pumpage will be less than any other alternative.

g. Collector wells with variable pumping rates

Another method of increasing efficiency is to vary the pumping rates of the wells over both time and space. Well 1 (the eastern most well on the golf course) is an essential part of the flow barrier, but does not remove much TCE from the system. By pumping more from well 2 and less from well 1, the composite concentration of TCE in the pumpage may be increased and the cost effectiveness of the system increased. Pumping more water from the wells at early times may also capture more of the contamination that is between the collection wells and the stream. The limit on this variation is the specific capacity of the collection wells; how much water will the well yield.

Half of the pumpage from well 1 was assumed to be pumped by well 2 (an additional 18 gpm). In addition, well 2 was pumped at a rate of 80 gpm for the first year, 60 gpm for the second year, and 54 gpm for the third year and thereafter. All other inputs to the flow model were the same as they were for the initial collection well scenario. The following well pumping rates were used:

Well	Column	Row	Pumping Rate (ft^3/day)
1	9	27	3465
2	17	28	15400 for 1st year
			11551 for 2nd year
			10396 beyond
3	23	30	6930

Each collector well was assumed to have a radius of 0.25 feet and fully penetrate the water table aquifer. The wells were assumed to be 100 percent efficient (no well loss). The flow model was run for five years with 60.833 day time steps. Figure III-35 shows a plot of water table elevation versus time for well 2. The bottom of the aquifer is assumed to be at an elevation of 650 feet. Steady state was reached at about three years. Figure III-36 shows the steady state water table with the continuous pumping for the third year and beyond. Steady state well drawdowns are:

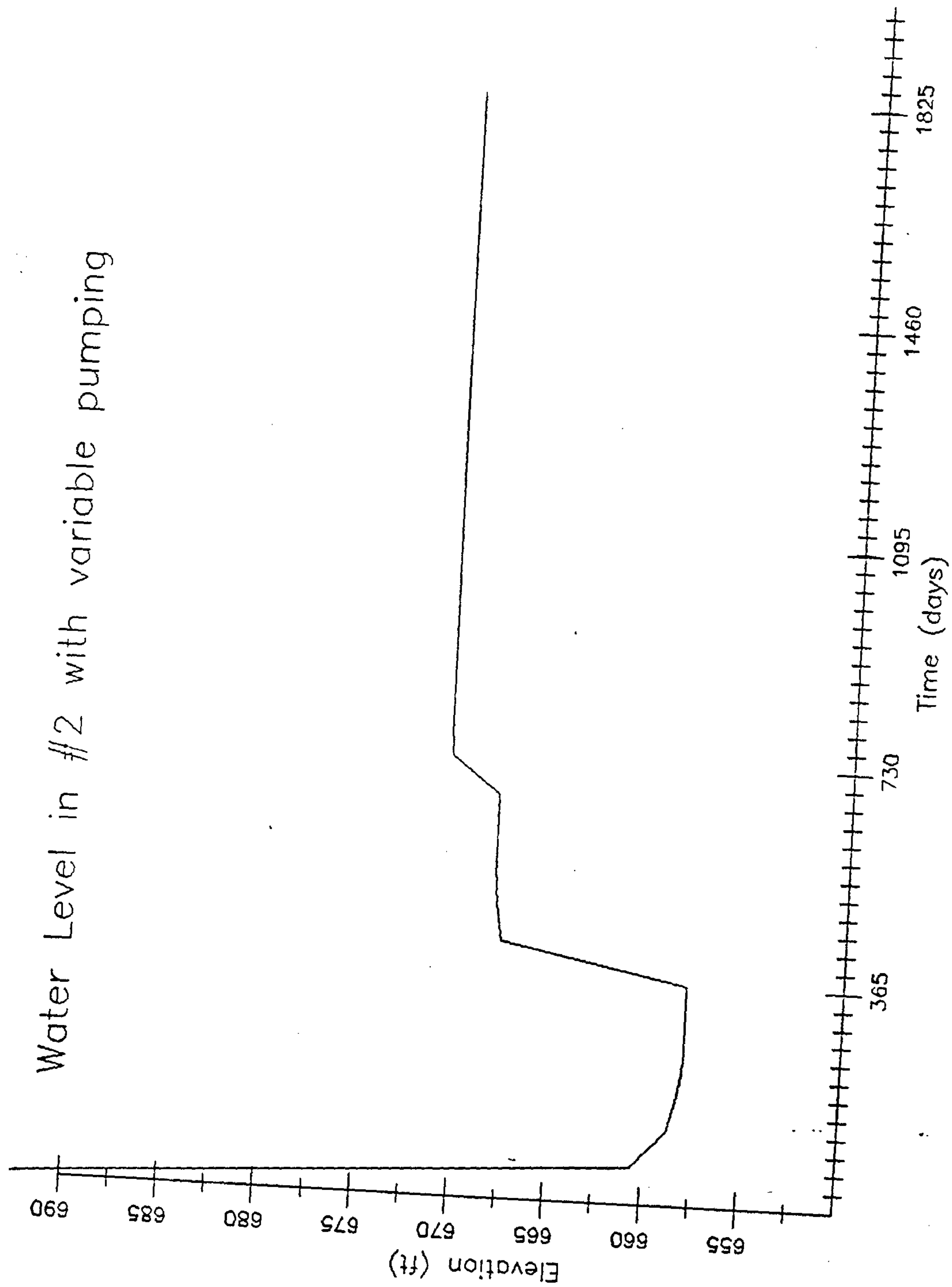

Figure III-35

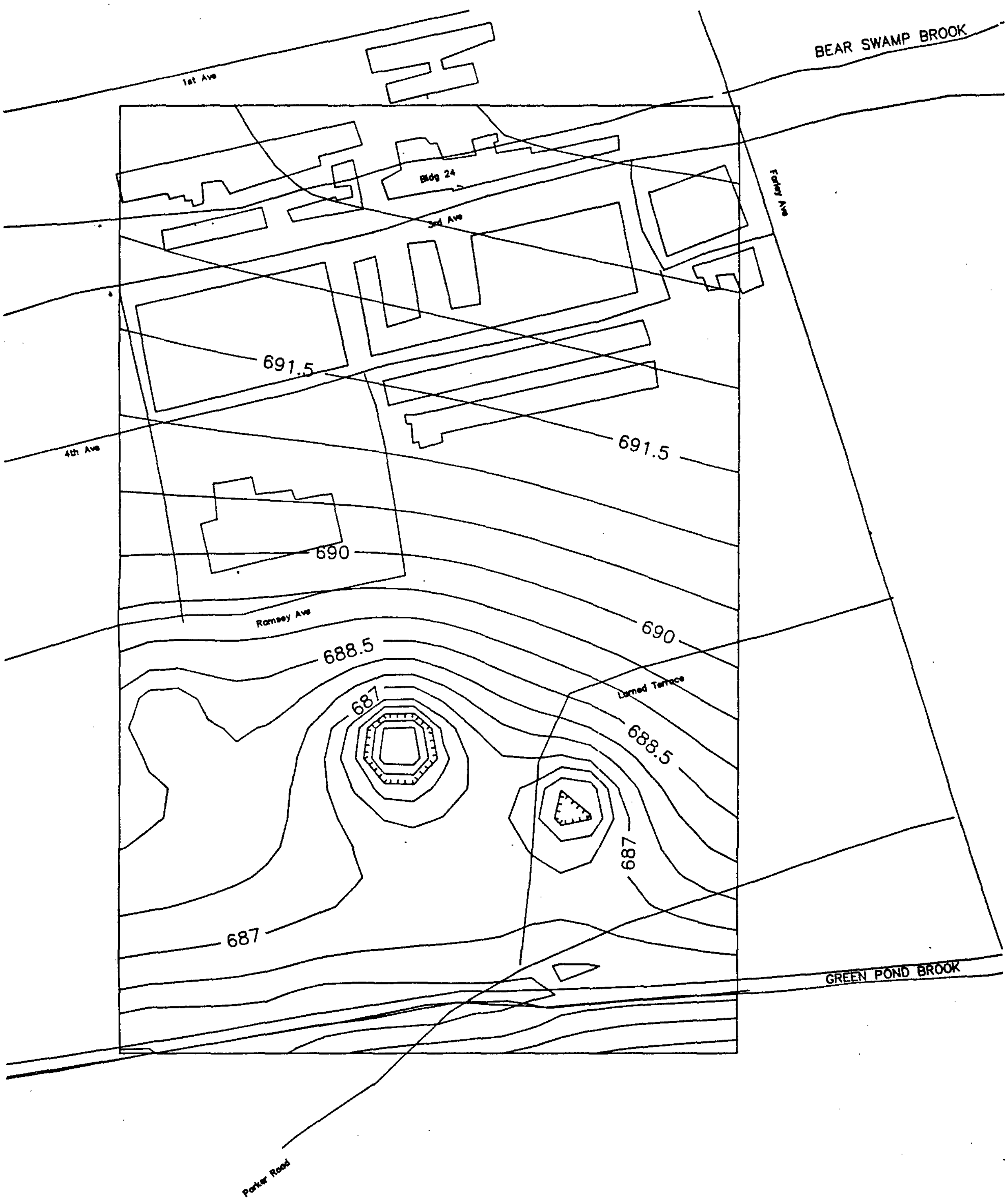

Figure III-36

WATER TABLE AQUIFER

DESIGNED DHK 2/89 DATE		
DRAWN PPM 2/89 DATE		
CHECKED ______ DATE		
APPROVED ______ DATE		

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PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

COLLECTION WELL SCENARIO
WITH VARIABLE PUMPING RATES
STEADY STATE WATER TABLE

SCALE 1"=200' | CONTRACT NO. 8313.10 | DATE 3/14/89 | SHEET

Well	Drawdown (ft)
1	6.4
2	19.5
3	12.6

Stream depletion at the end of the first year is 42 gpm (0.09 cfs). Steady state stream depletion is 34 gpm (0.076 cfs).

PREMOD3D was used to generate velocity files at intervals of 60.833 days. The resulting velocity files were input to RAND3D. The solute transport parameters were as discussed previously (9573 particles with a weight of 0.04314 lbs each). The model was run for 27 years. Time steps of 60.833 days were used for the first three years to simulate a transient flow field. A time step of one year was used up to twelve years, followed by three time steps of five years.

Figure III-37 shows the rate of TCE removal from the aquifers by the wells and the stream. After three years of pumping, 88 percent of the TCE has been removed from the aquifer, with 85 percent being removed by the collection wells and three percent entering Green Pond Brook. Figure III-38 shows the TCE concentrations in the water table aquifer. After six years of pumping, 95 percent of the TCE has been removed, with 92 percent being removed by the wells and three percent entering the stream. At this point, the water table aquifer is almost free of contamination, but some TCE is still moving through the confining layer into the confined glacial aquifer. At the end of twenty seven years of simulation, approximately three percent of the initial contamination is still in the aquifer system.

Figure III-39 shows the TCE concentrations in the pumpage for each of the wells. Well 2 has the highest concentrations since it is in the middle of the plume. Well 3 also intersects the edge of the plume. Figure III-29 shows the composite concentration of TCE that will be treated. One hundred and thirty-four gpm will be pumped the first year, one hundred and fourteen gpm will be pumped the second year, and one hundred and eight gpm will be pumped in succeeding years. Initially, concentrations of TCE in the pumpage will be high, over 700 ppb. TCE concentrations will decline rapidly over time and probably be less than 100 ppb at the end of two years. At the end of ten years, concentrations are less than 5 ppb.

Figure III-30 shows TCE concentrations in the seepage to Green Pond Brook over time. The initial concentrations are approximately 40 ppb. TCE concentrations in stream seepage decline rapidly; at the end of a year they are less

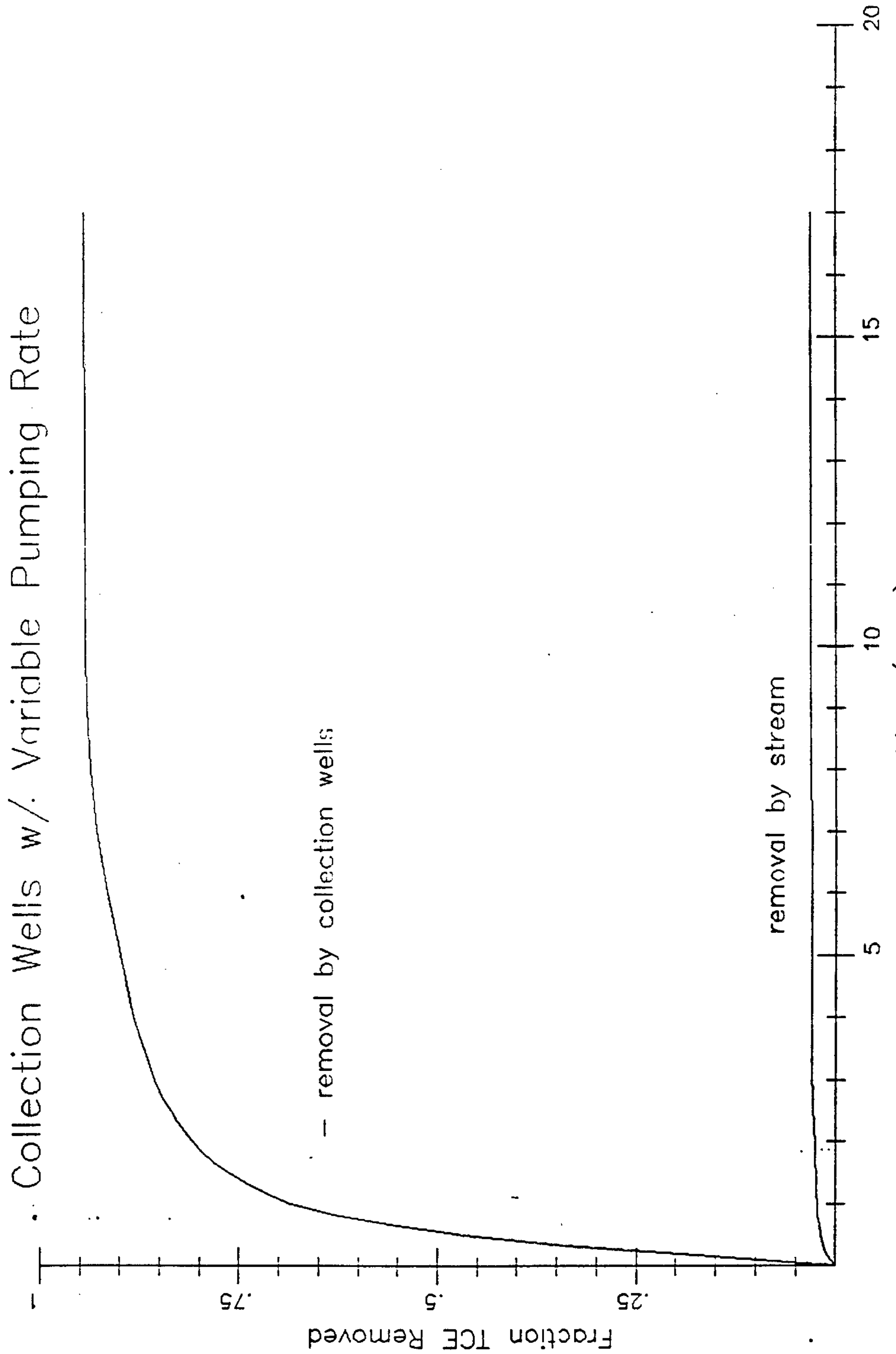

Figure III-37

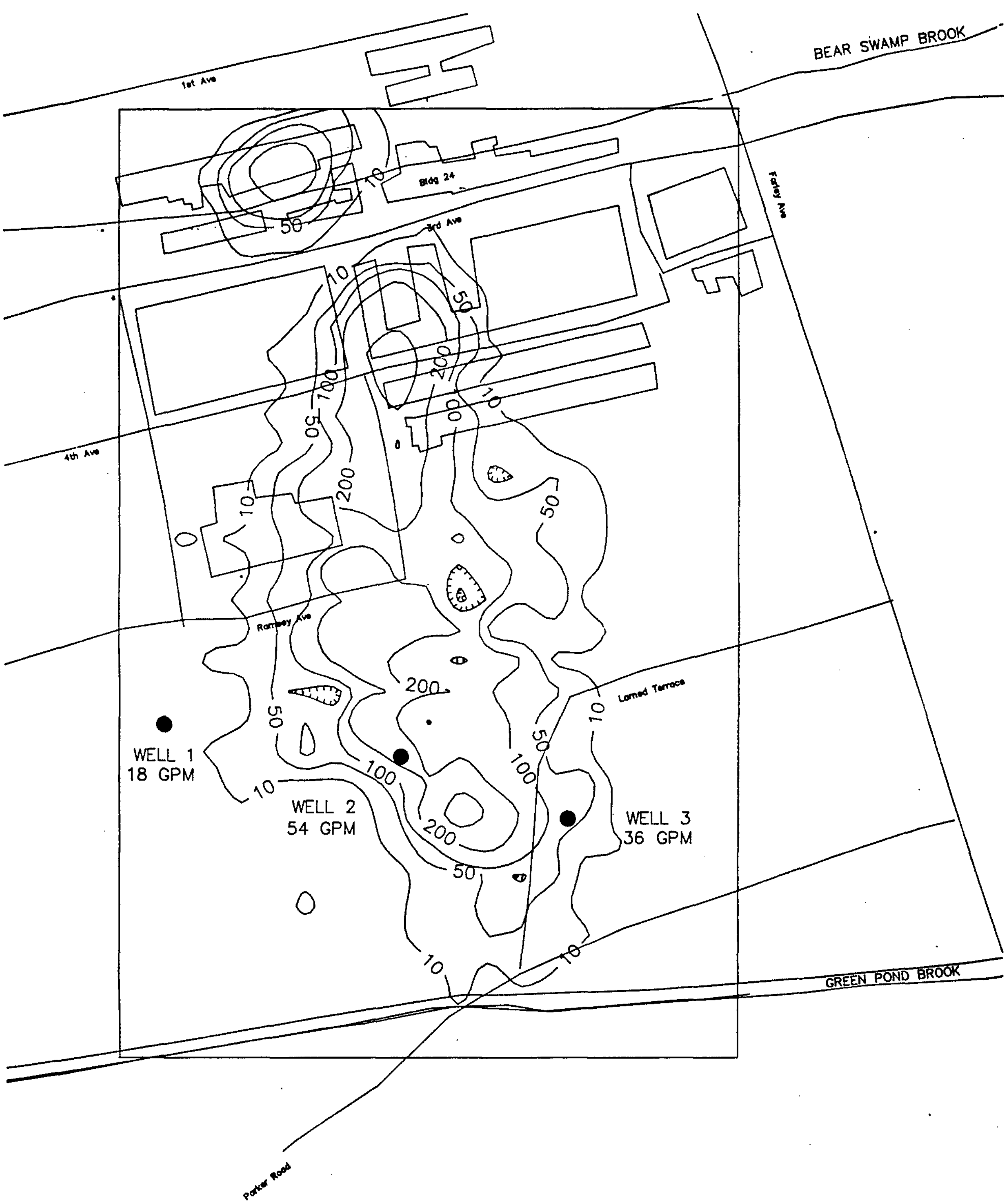

Figure III-38

WATER TABLE AQUIFER

DESIGNED DHK 2/89 DATE DRAWN PPM 2/89 DATE CHECKED ____ DATE APPROVED ____ DATE	ENGINEERING TECHNOLOGIES ASSOCIATES, INC. ENGINEERS • PLANNERS • SURVEYORS ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING COLLECTION WELL SCENARIO WITH VARIABLE PUMPING RATES TCE CONCENTRATIONS (ppb)–YEAR 3 SCALE 1"=200' CONTRACT NO. 8313.10 DATE 3/21/89 SHEET

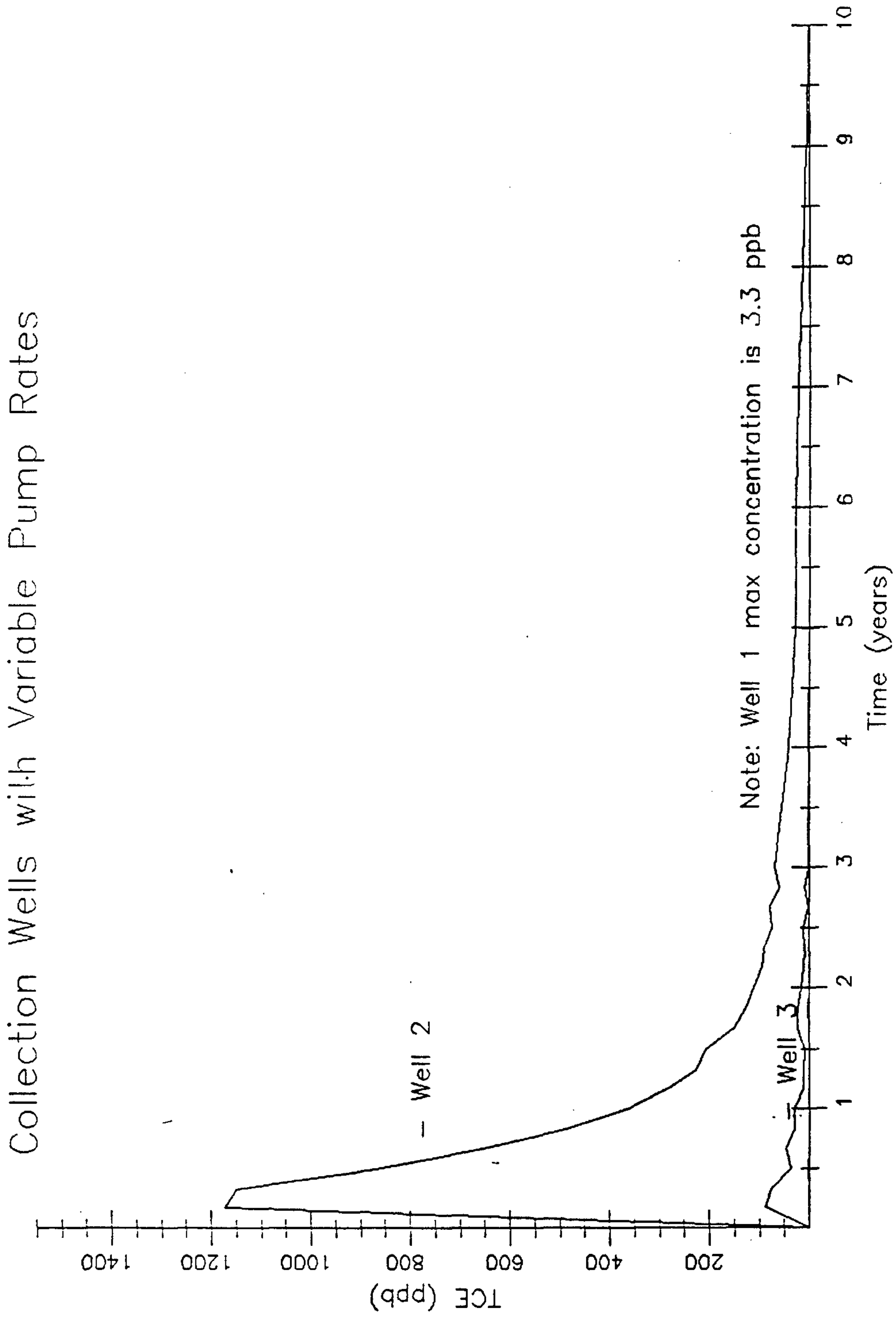

Figure III-39

than 10 ppb. Some small amount of TCE still reaches the stream over time. The unevenness in the graph is due to the random nature of the model; relatively few particles reach the stream, thus the random nature of the dispersion algorithm causes the predicted concentrations to fluctuate in time. Assuming an average flow for Green Spring Brook of about six cfs, the maximum instream concentration of TCE would be about 2 ppb.

This alternative maximizes the concentration of TCE in the pumpage and is also relatively effective in preventing TCE from entering the stream. It will require a large treatment facility, however, because of the high TCE concentrations with larger volume of ground water pumped. It also does not create as effective a barrier to contamination as the other scenarios. The barrier is quite effective in the water table aquifer, but the reduced pumping rate at well 1 results in less of a barrier in the confined glacial aquifer. With equal amounts of pumping from the three wells, most contamination in the confined glacial aquifer moves up in the confining layer towards the collection wells. In this scenario, with reduced pumping in well 1, some contamination may travel beneath well 1 and move up in the confining layer under Green Pond Brook.

4. Sensitivity Analysis

a. Introduction

Sensitivity analysis is an important part of any modeling study. Sensitivity analysis defines how the uncertainty in the input parameters affects the conclusions of the study. The sensitivity of assumptions regarding hydraulic conductivity, dispersivity, initial pollutant distribution, and retardation was examined for both the no action scenario and the collection wells with variable pumping. There are many other parameters that are subject to considerable uncertainty, but these are believed to be the most significant.

These parameters were changed in selected scenarios and the model rerun. It was not necessary to rerun all the scenarios with all the parameter changes. After running one or two scenarios, it was possible to deduce how that parameter affected the other scenarios. Most of the sensitivity runs were made with the no action scenario and the collection wells with variable pumping scenario.

b. Retardation coefficient

Adsorption is one of the factors in the model subject to considerable uncertainty. As previously explained, the RAND3D model assumes a linear, reversible adsorption isotherm, thus adsorption is simulated using a retardation

coefficient. The initial assumption was that there was no adsorption in the aquifer layers, and some adsorption was present in the confining layers (retardation factor of 1.5). Analysis of the TCE plume extent and known dates of TCE use indicates that the maximum probable value of retardation in the water table aquifer is about three. A value of three was used in the aquifer layers for the sensitivity analysis. A value of ten was used in the confining layers.

It is not necessary to rerun the no action alternative to see the effect of increased retardation. The plume will move through the water table aquifer three times slower than it was initially simulated to move. On the plot (Figure III-14) of TCE removal from the aquifer versus time, multipling the ordinates of the x axis by a factor of three (ignoring the impact of greater retardation in the confining layer), yields a fair representation of TCE removal from the water table aquifer with an assumption of more adsorption and the no action scenario.

The collection wells with variable pumping rates scenario requires simulation to see the effect of greater retardation. Retardation causes the plume to move much more slowly, which lets the collection well zone of influence expand to its steady state value before some of the contamination reaches Green Pond Brook. Thus, the collection wells may be more effective in protecting Green Pond Brook from TCE, but it will take much longer to clean up the aquifer. Figure III-40 shows the pollutant removal versus time for the collection wells with variable pumping rate scenario with larger retardation coefficients. After three years of pumping, 65 percent of the TCE has been removed from the aquifer, with 63 percent being removed by the collection wells and two percent entering Green Pond Brook. After seven years of pumping, 84 percent of the TCE has been removed, with 81 percent being removed by the wells and three percent entering the stream. After fifteen years of pumping, 91 percent of the TCE has been removed, with 88 percent removed by the wells, and three percent entering the stream.

The peak concentration of TCE in the ground water seeping into Green Pond Brook is about 80 ppb. This is approximately twice the TCE concentration in seepage in the base case for the collection wells with variable pumping scenario. This result is a consequence of assuming that there is three times as much TCE actually in the water table aquifer at the beginning of the simulation. The initial amount of TCE is three times as high, yet peak TCE concentrations in seepage are only twice as much. The collector wells are actually more efficient with the assumption of high retardation because the cone of depression formed by the collection wells expands at the

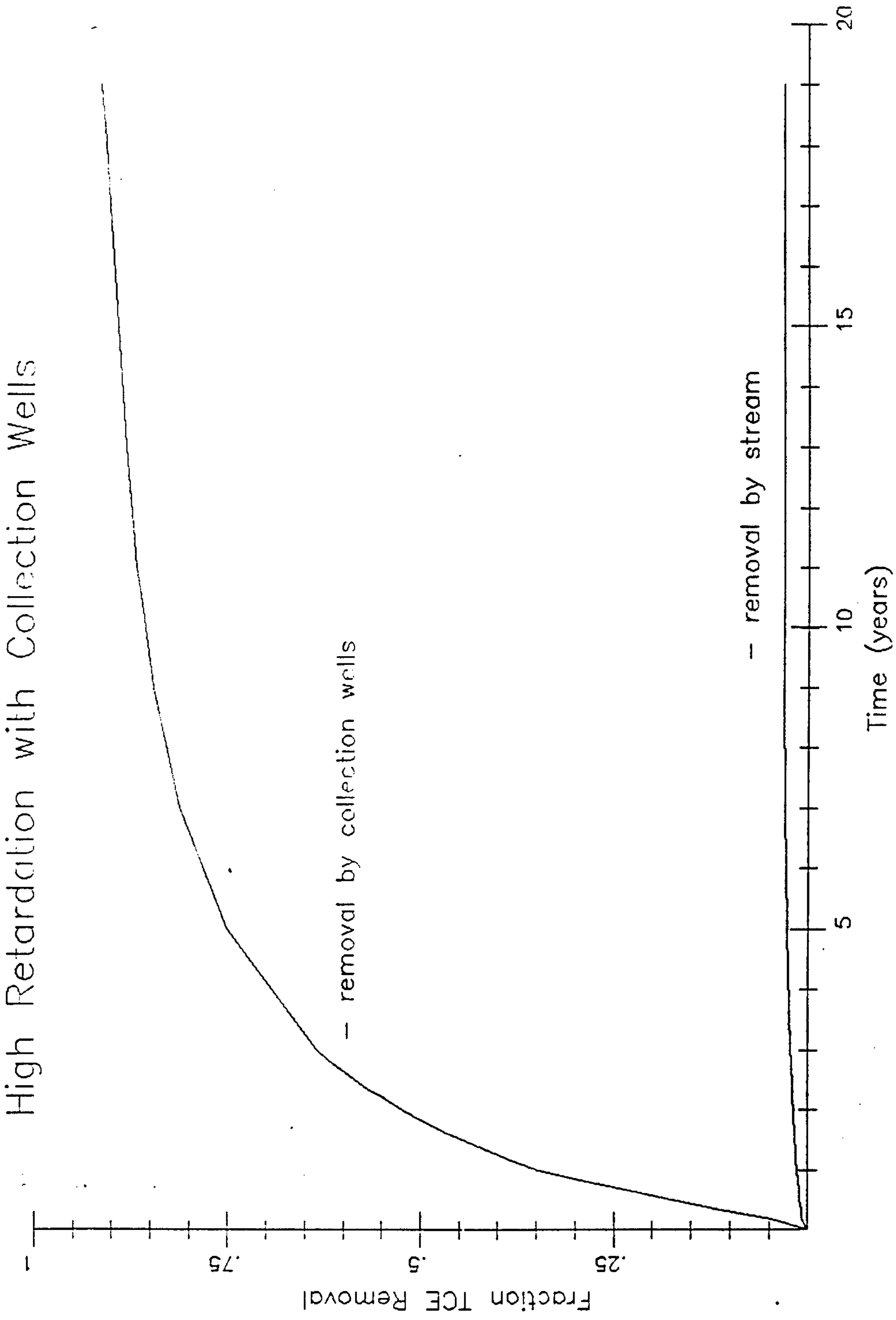

Figure III-40

same rate, but the TCE moves at one-third the speed, thus the collection wells eventually gather more. The peak composite concentration of TCE in the pumpage is 820 ppb and 690 ppb at the end of the first year. With the base assumptions, the peak composite TCE concentration was 724 ppb and 225 ppb at the end of the first year.

This sensitivity analysis indicates that if the base assumption regarding the adsorption of TCE in the water table aquifer is incorrect, i.e. retardation is a significant factor affecting TCE movement, the collection well scenarios will still be effective in removing TCE from the aquifers and preventing TCE from reaching Green Pond Brook. Aquifer cleanup will take much longer if this assumption is true.

c. Dispersivity

Dispersivity is a parameter that was selected based on experience and simple calculations. It is typically assumed to be a measure of the small scale heterogeneity of the aquifer. Both higher and lower values of dispersivity were tested with both the no action and collection wells with variable pumping scenarios. The higher values of dispersivity in the analysis were ten times the base values. The longitudinal dispersivity was changed to 100 feet, the transverse dispersivity became 30 feet, and the vertical dispersivity became 1.0 feet. Then dispersivity was changed to zero for all three directions and the scenarios run again.

Figures III-41 and III-42 show the TCE concentrations in the water table aquifer at a time of four years under the no action scenario with the higher and lower dispersivities. High dispersivity causes the plume to spread out unrealisticly. The impact of assuming a dispersivity of zero is hard to perceive because the plume spread out (by dispersion) at its starting position. For comparison the base case in shown on Figure III-43.

Figures III-44 and III-45 show the impact of dispersivity on the flushing of TCE from the aquifer under the no action scenario. With dispersivities ten times the base assumptions, after two years, 16 percent of the TCE has entered Green Pond Brook. After ten years, 52 percent of the TCE has entered the stream. With a dispersivity of zero, after two years, 19 percent of the TCE has entered Green Pond Brook. After ten years, 86 percent of the contamination has entered the stream.

The peak concentrations of TCE in stream seepage (averaged over the modeled stream reach) from the water table aquifer are about 100 ppb for the zero dispersivity case and 46 ppb for the high dispersivity case.

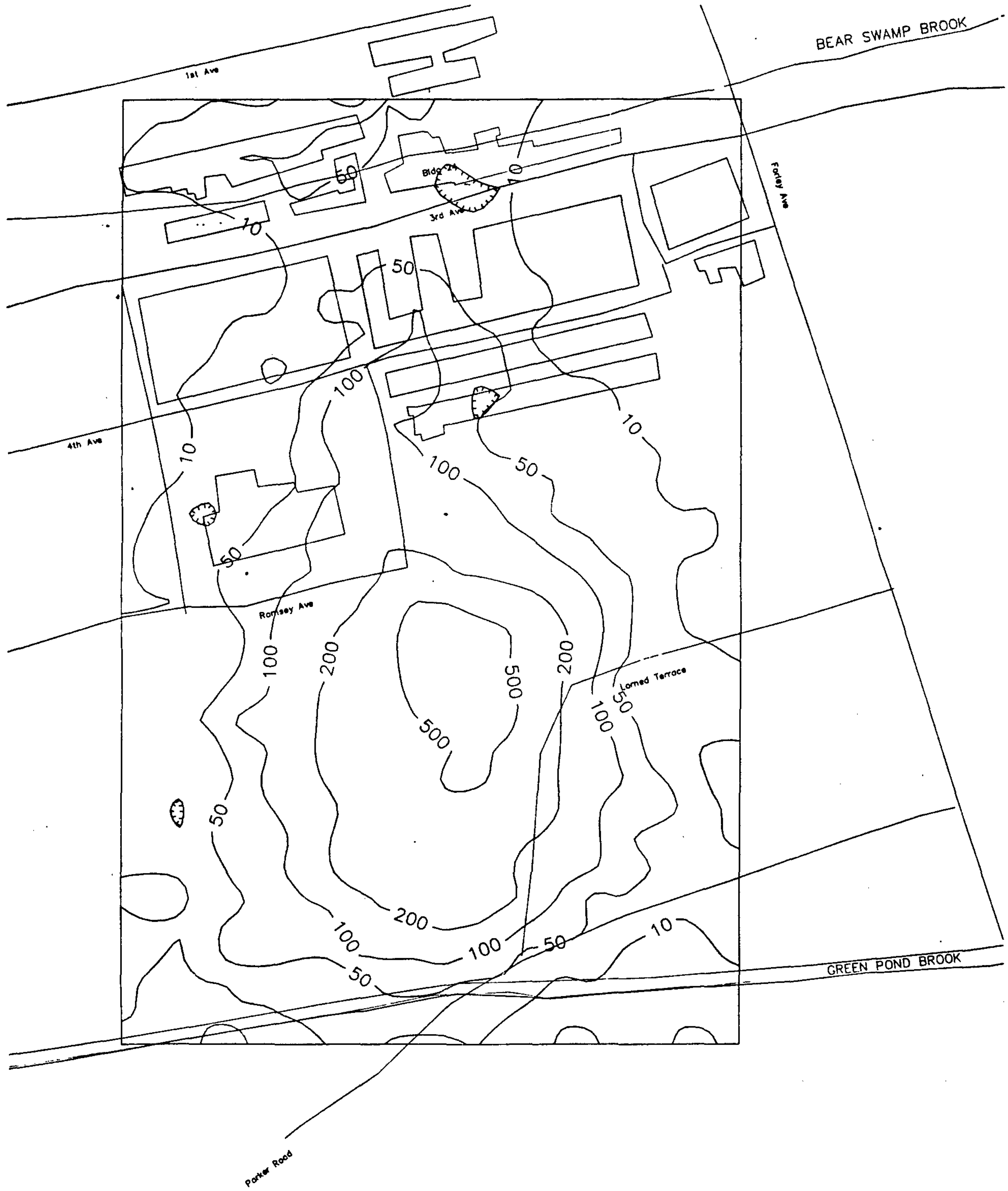

Figure III-41

WATER TABLE AQUIFER

DESIGNED	DHK 3/89
DRAWN	PPM 3/89
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PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

SENSITIVITY ANALYSIS – HIGH DISPERSIVITY
NO ACTION SCENARIO
TCE CONCENTRATIONS (ppb) – YEAR 4

SCALE: 1" = 200' | CONTRACT NO.: 8313.10 | DATE: 3/27/89 | SHEET:

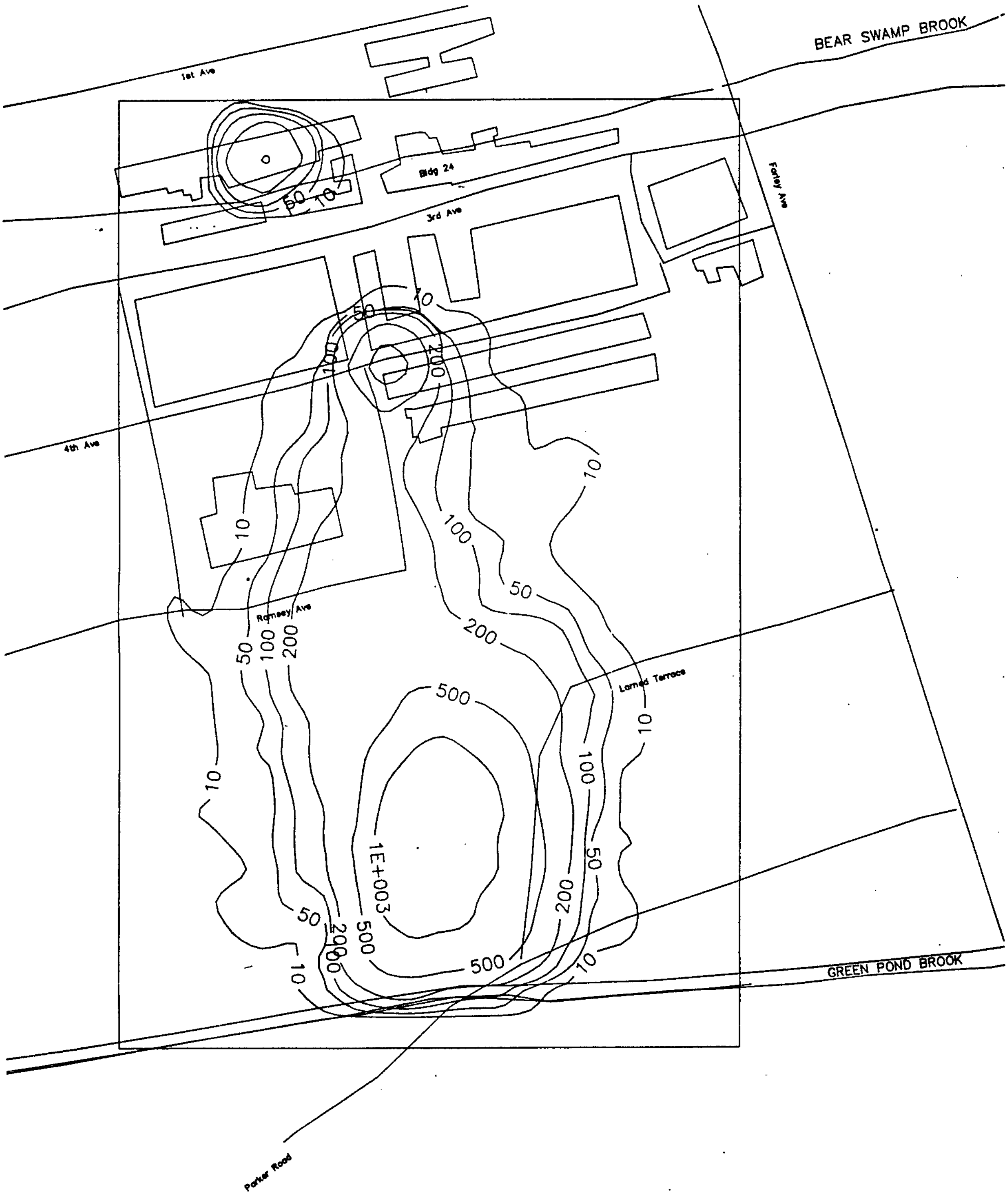

Figure III-42

WATER TABLE AQUIFER

DESIGNED	DHK	3/89	DATE
DRAWN	PPM	3/89	DATE
CHECKED			DATE
APPROVED			DATE

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PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

SENSITIVITY ANALYSIS – LOW DISPERSIVITY
NO ACTION SCENARIO
TCE CONCENTRATIONS (ppb) – YEAR 4

SCALE: 1"=200' | CONTRACT NO.: 8313.10 | DATE: 3/27/89 | SHEET:

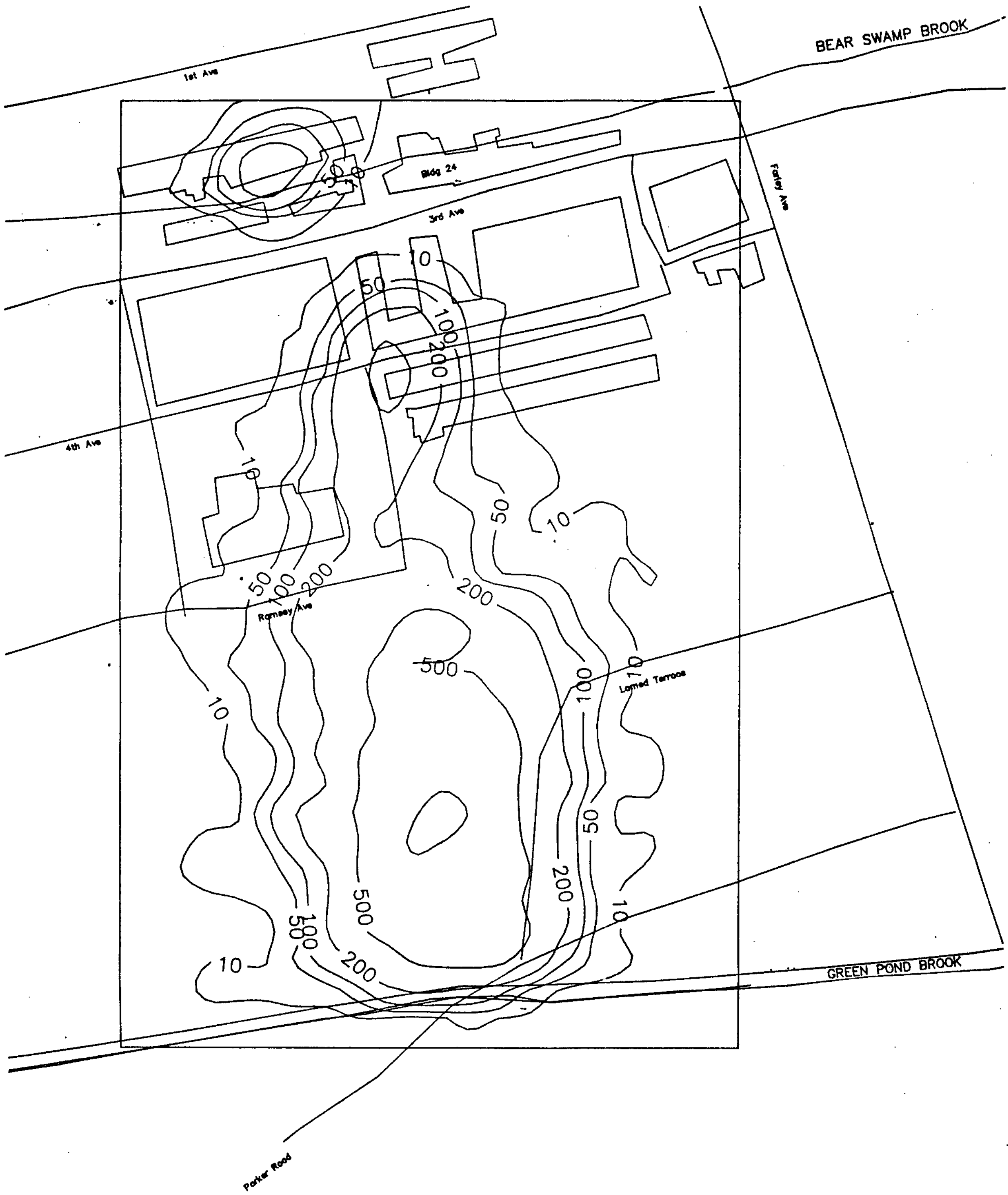

Figure III-43

DESIGNED	DHK	2/89	
DRAWN	PPM	2/89	
CHECKED			
APPROVED			

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PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

NO ACTION SCENARIO

TCE CONCENTRATIONS (ppb)—YEAR 4

SCALE 1"=200' | CONTRACT NO. 8313.10 | DATE 3/8/89 | SHEET

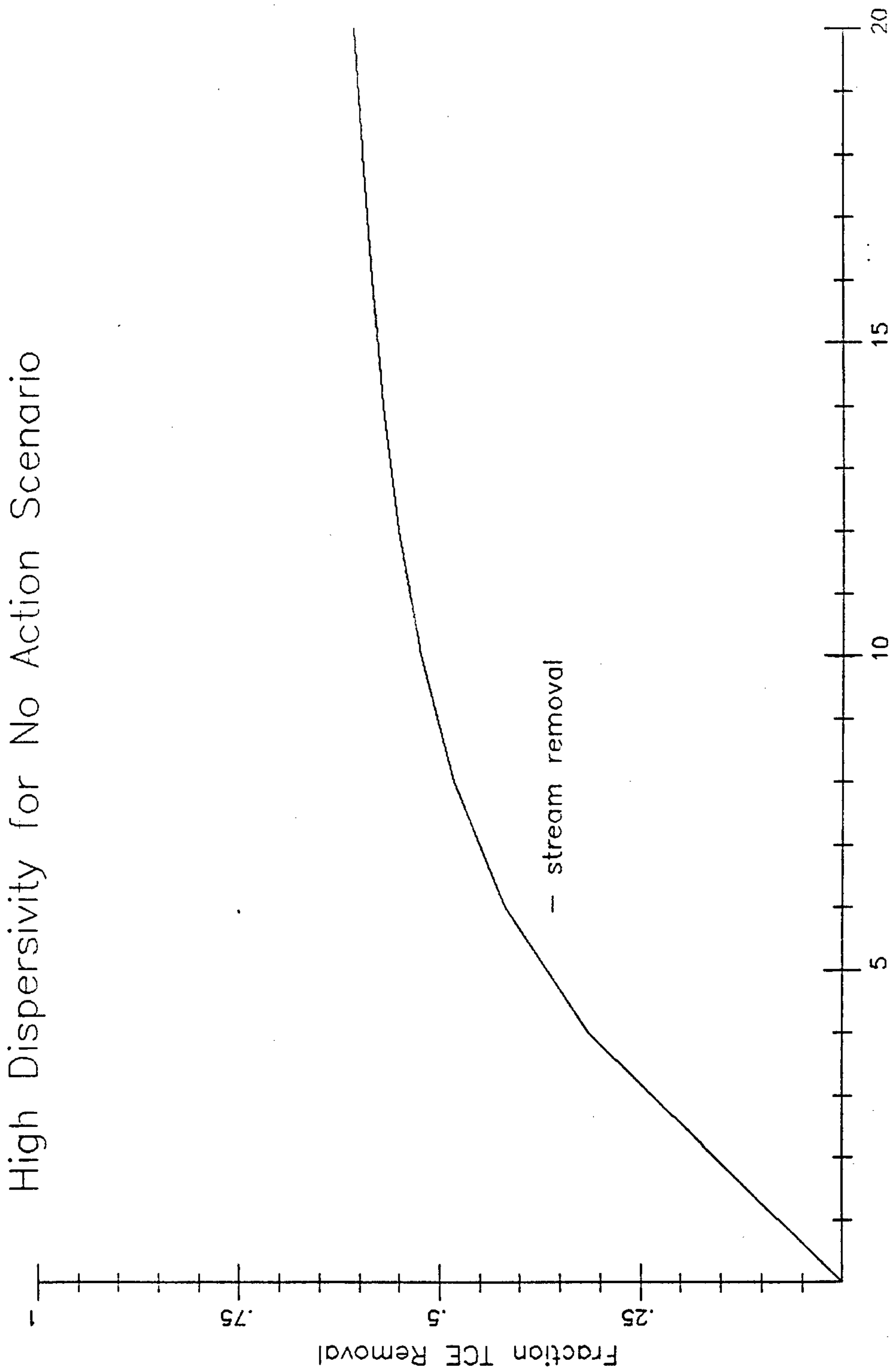

Figure III-44

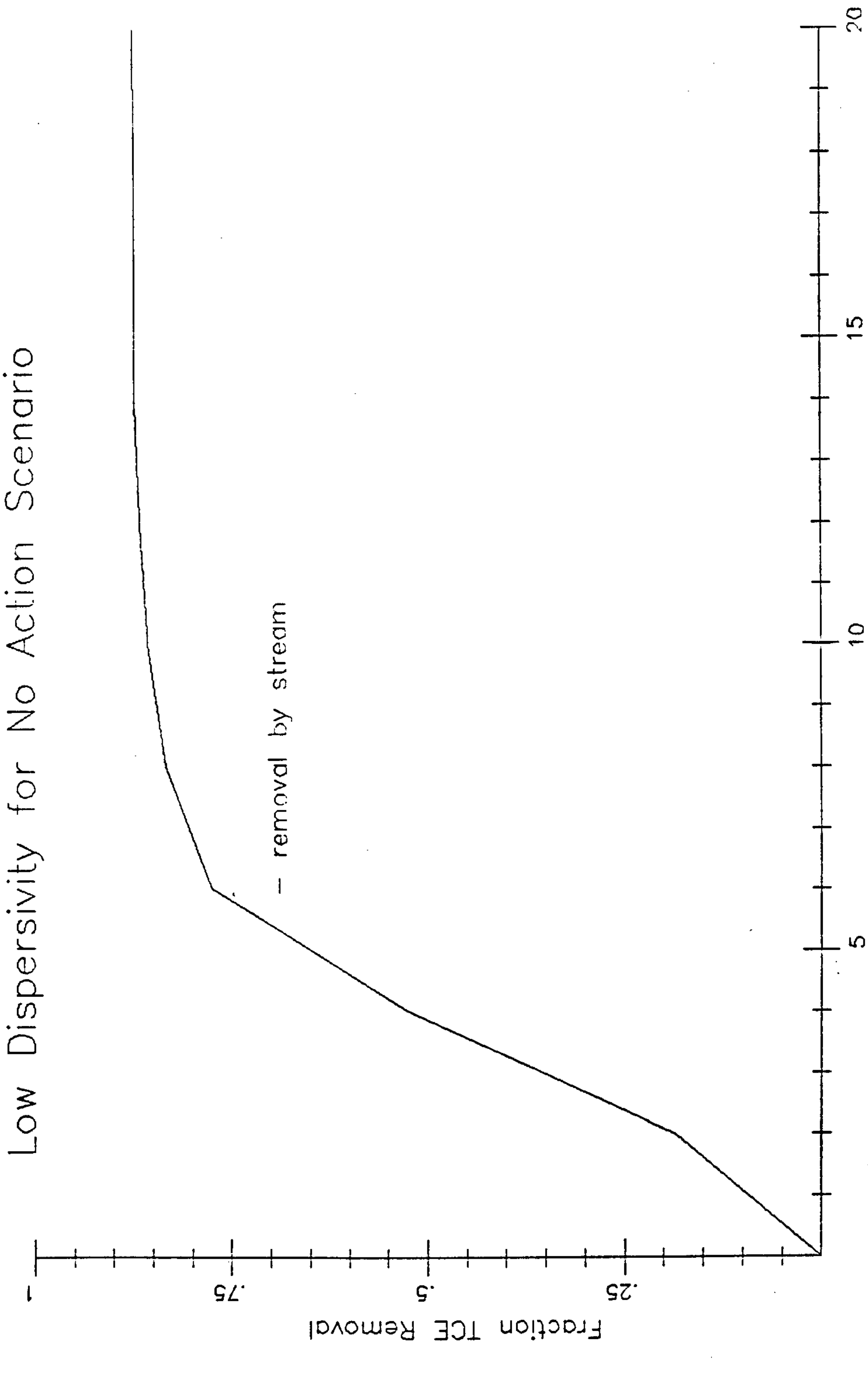

Figure III-45

Figures III-46 and III-47 show the impact of dispersivity on the flushing of TCE from the aquifer under the collection wells with variable pumping scenario. With a dispersivity of zero, after three years, 90 percent of the TCE has been removed from the aquifers with 87 percent removed by the collector wells and three percent entering Green Pond Brook. After six years, 95 percent has been removed from the aquifers with 92 percent removed by the wells and three percent by the stream. With dispersivities ten times the base assumptions, after three years, 42 percent of the TCE has been removed from the aquifers with 35 percent removed by the collector wells and seven percent removed by the stream. After six years, 75 percent has been removed from the aquifers with 50 percent removed by the wells and 15 percent by the stream.

Figures III-48 and III-49 show the TCE concentrations in the water table aquifer at a time of three years with the collection wells with variable pumping scenario with the higher and lower dispersivities. High dispersivity causes the plume to spread out in an unrealistic fashion. The zero dispersivity analysis shows the streamlines of flow to the wells.

The peak concentrations of TCE in stream seepage (averaged over the modeled stream reach) from the water table aquifer with variable pumping of the collection wells are insensitive to the value of dispersivity.

The impact of dispersivity on the conclusions of this modeling study is small. Larger dispersivity causes particles to disperse away from the direction of flow. Larger dispersivity thus causes the TCE to travel farther to reach collection wells or a stream because it will follow a more convoluted path. The model results indicate that the collection wells will be less effective with a larger dispersivity. This result is partly true, and partly a function of the unrealistic dispersivity assumed for the high dispersivity case and the model algorithm. The model only permits a particle to enter a sink (well or stream node) when the particle is less than the maximum move distance if the dispersion movement is much larger than this maximum move and time steps are not extremely small, particles may pass over a well. This result is not realistic, and should not be considered a possible outcome.

d. Pollutant Source

One of the major assumptions of the base model scenarios is the initial distribution of TCE in the water table and confined glacial aquifers. It was assumed that no more TCE was entering the water table aquifer. If this is true, it is entirely fortuitous. The TCE plume is moving towards Green Pond Brook; the fact that large TCE

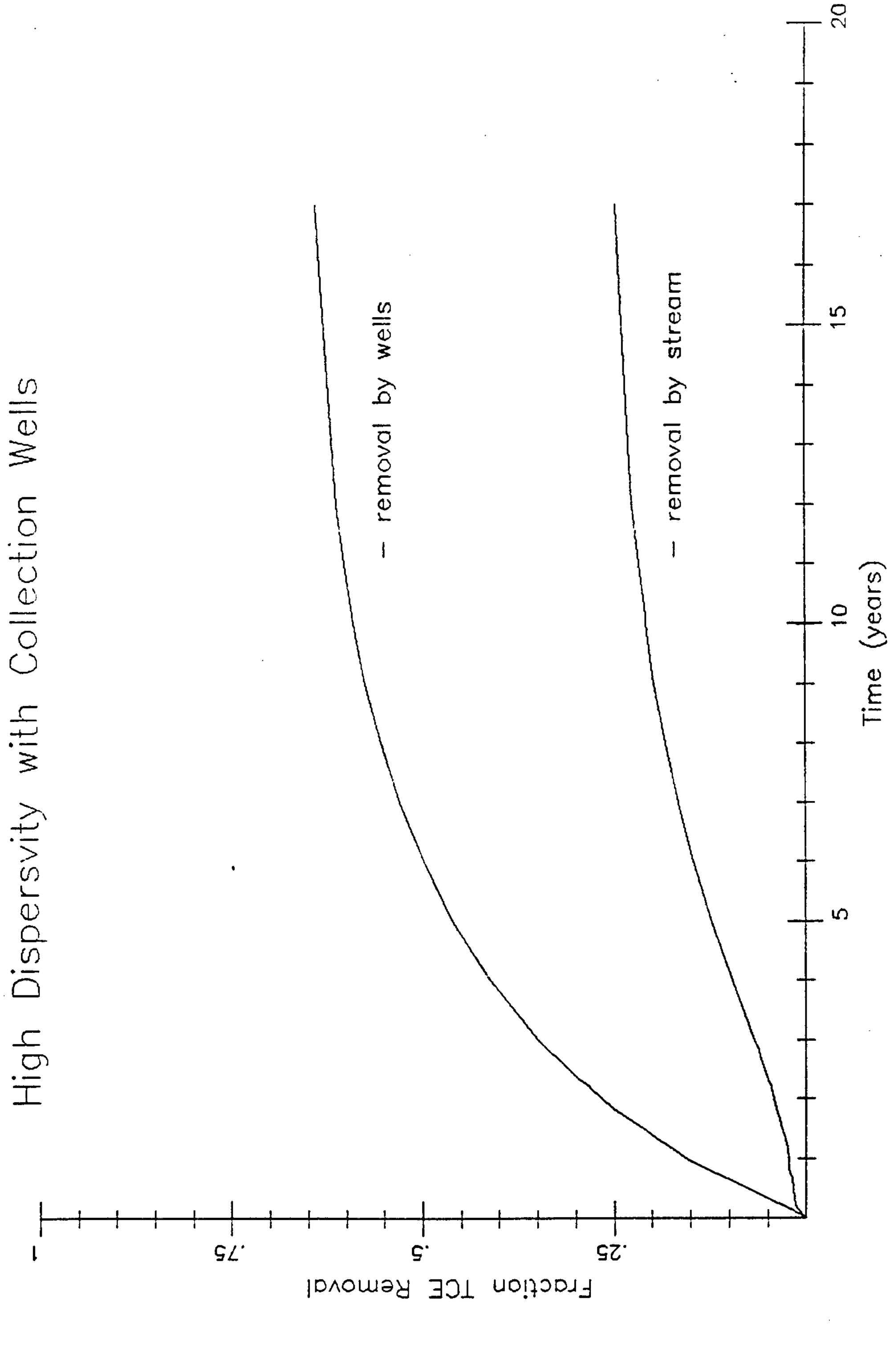

Figure III-46

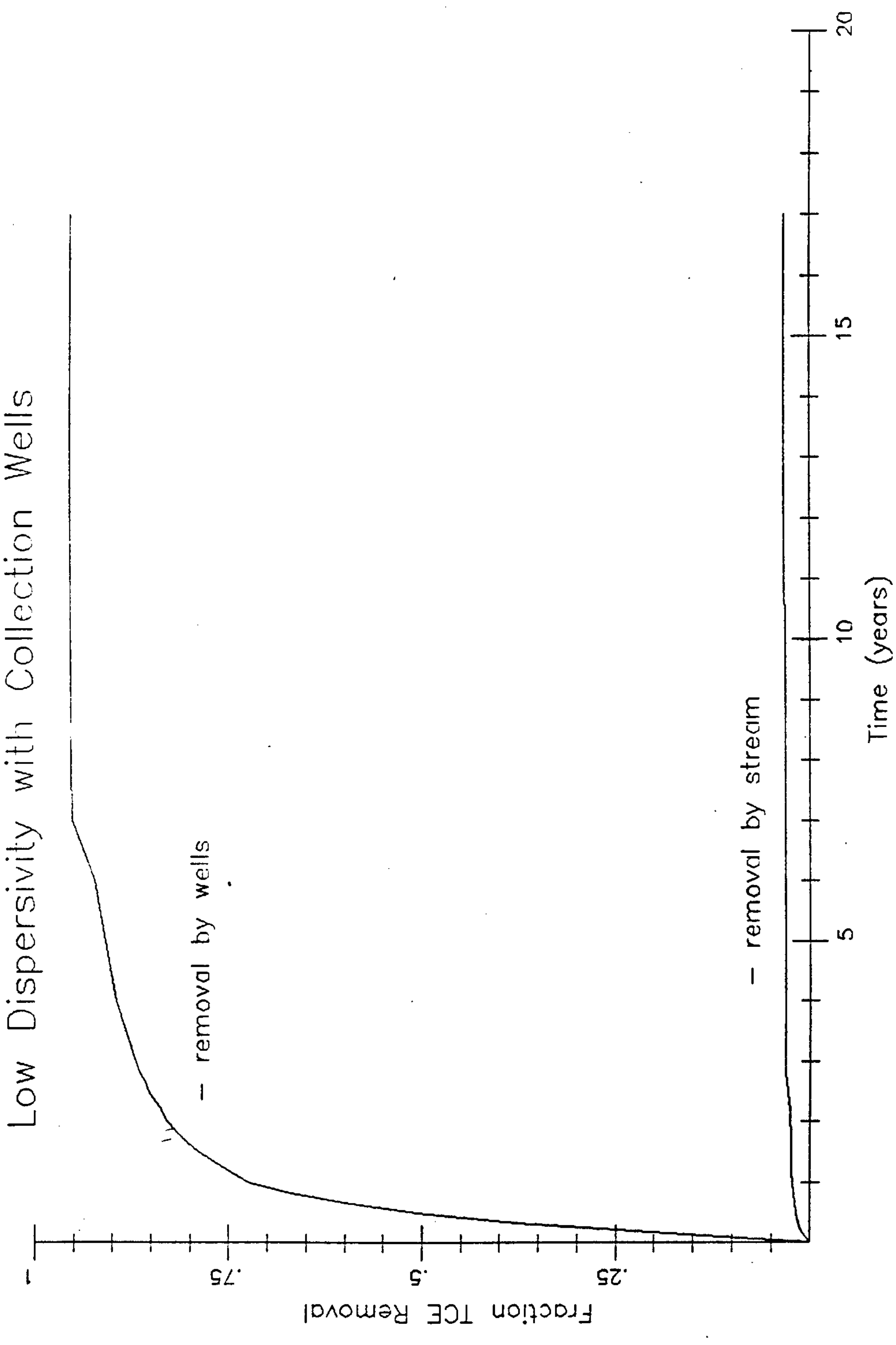

Figure III-47

Figure III-48

WATER TABLE AQUIFER

DESIGNED	DHK	2/89	ENGINEERING TECHNOLOGIES ASSOCIATES, INC.
DRAWN	PPM	2/89	ENGINEERS • PLANNERS • SURVEYORS
CHECKED			
APPROVED			

PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

SENSITIVITY ANALYSIS – LARGE DISPERSIVITY

COLLECTION WELLS WITH VARIABLE PUMPING

TCE CONCENTRATIONS (ppb) – YEAR 3

SCALE: 1"=200' | CONTRACT NO.: 8313.10 | DATE: 3/21/89 | SHEET:

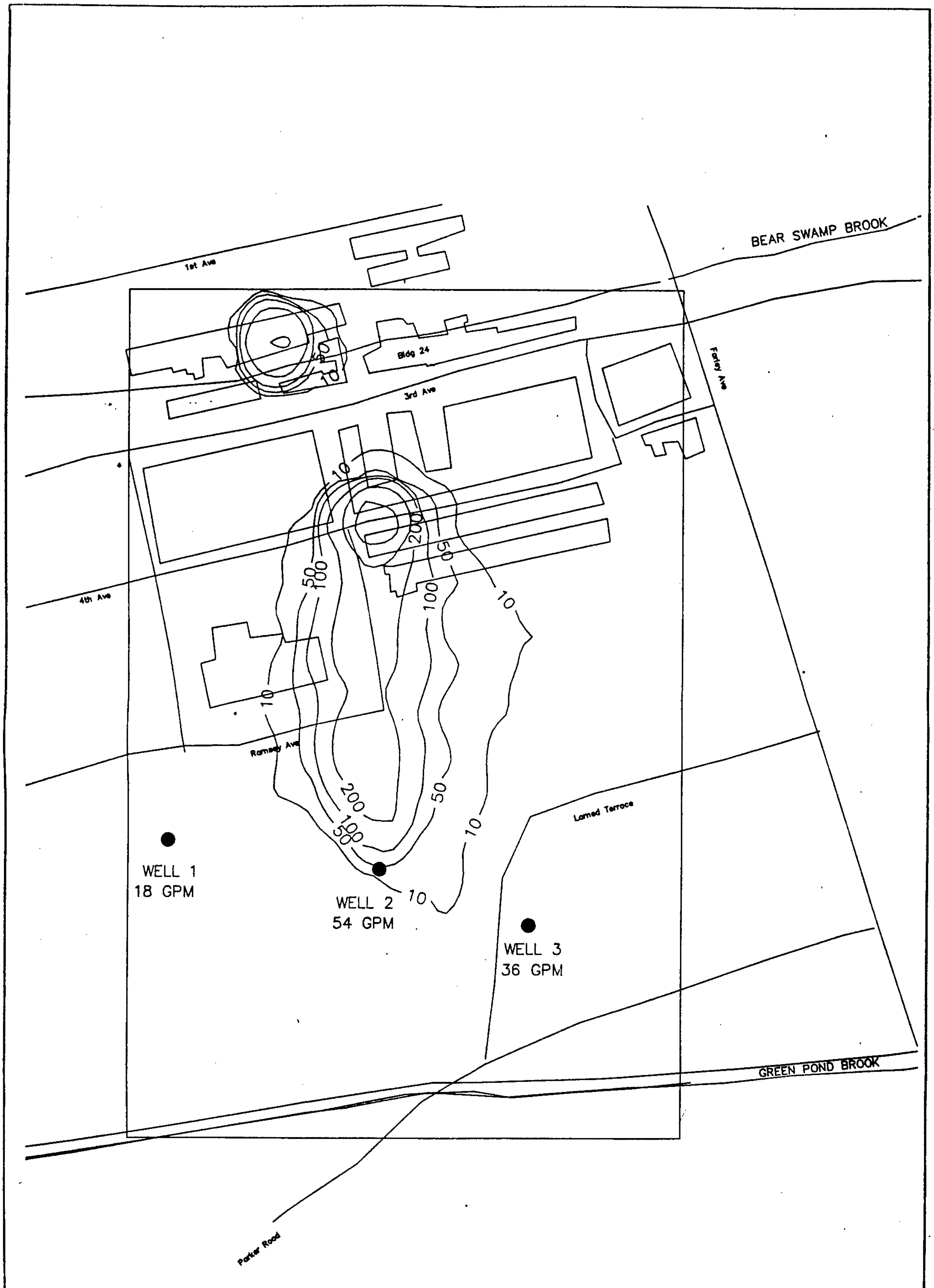

Figure III-49

WATER TABLE AQUIFER

DESIGNED DHK 2/89	ENGINEERING TECHNOLOGIES ASSOCIATES, INC.	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING
DRAWN PPM 2/89	ENGINEERS • PLANNERS • SURVEYORS	SENSITIVITY ANALYSIS – LOW DISPERSIVITY
CHECKED	3458 ELLICOTT CENTER DRIVE SUITE 101	COLLECTION WELLS WITH VARIABLE PUMPING
APPROVED	ELLICOTT CITY, MARYLAND 21043	TCE CONCENTRATIONS (ppb) – YEAR 3
		SCALE 1"=200' CONTRACT NO. 8313.10 DATE 3/21/89 SHEET

concentrations are still present near Building 24 indicates that TCE is probably still entering the aquifer, although probably in smaller amounts. The most likely source of this additional TCE is deadsorption in the unsaturated zone. The unsaturated zone is likely to contain more organic carbon than the aquifer, and the organic carbon would adsorb TCE. Recharge would eventually leach the TCE from the soil and cause it to enter the water table aquifer. Assuming a linear, reversible adsorption isotherm, a finite amount of TCE, and a constant rate of recharge, the amount of TCE entering the aquifer will decline exponentially with time (a first order process). The assumption of a continuous source of declining strength was added to the model to test the collection wells with variable pumping scenario.

The source of TCE at Building 24 was assumed to emanate from a 500 by 100 foot area around Building 24. The initial concentration of TCE in the recharge in this area was assumed to be 6000 ppb. The source was assumed to decay exponentially with a half life of five years. This assumption was added to the RAND3D model by adding particles to the model at each time step. During the first 60.833 day time step, 3.6 lbs of TCE were added to the water table aquifer. Over a 52 year simulation period, 157 lbs of TCE were added to the water table aquifer at Building 24.

This sensitivity scenario was run for 52 years using the parameters described for the collection wells with variable pumping scenario. Figure III-50 shows the fraction of TCE removed from the aquifer by the wells and Green Pond Brook versus time. The fraction removed was computed as the total amount removed divided by the total amount currently in the aquifer. Since TCE is continuously being added to the aquifer, removal does not approach 100 percent as rapidly as in other scenarios.

Figure III-51 shows the TCE concentrations in the water table aquifer at three years. The impact of the continuous source at Building 24 on TCE concentrations is easily discerned.

The TCE concentration in stream seepage is insensitive to the addition of a continuous source of TCE at Building 24. The collector wells form a barrier to the movement of TCE in the water table aquifer; the amount of TCE passing the collector well barrier is negligible.

This sensitivity analysis demonstrates that the collection wells provide an effective barrier to TCE movement between Building 24 and Green Pond Brook even if there is still a source of TCE in the aquifer. Some of the TCE still reaches Green Pond Brook. Some of the TCE travels vertically through the water table aquifer, through the confining layer, and then horizontally through the confined

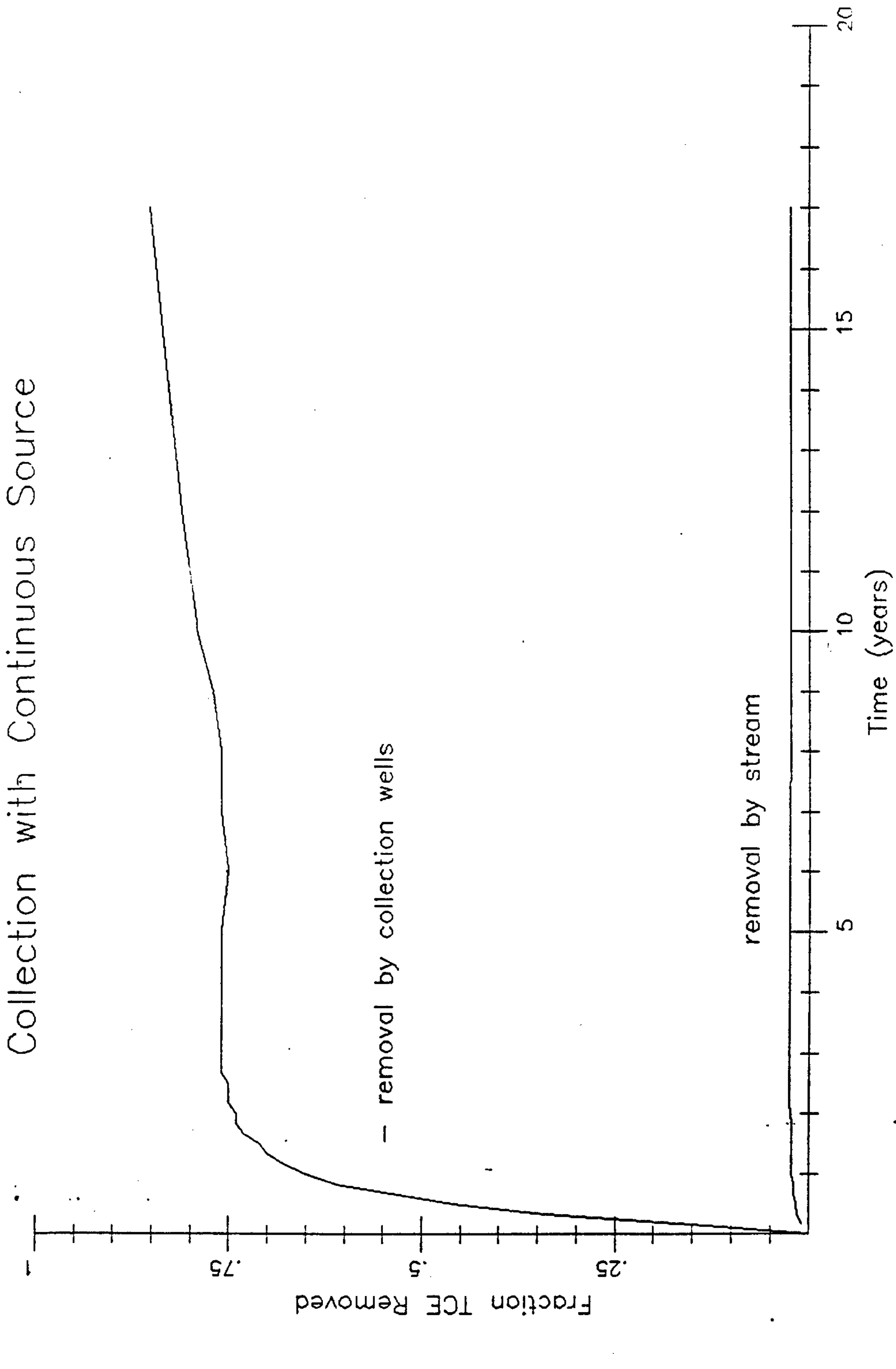

Figure III-50

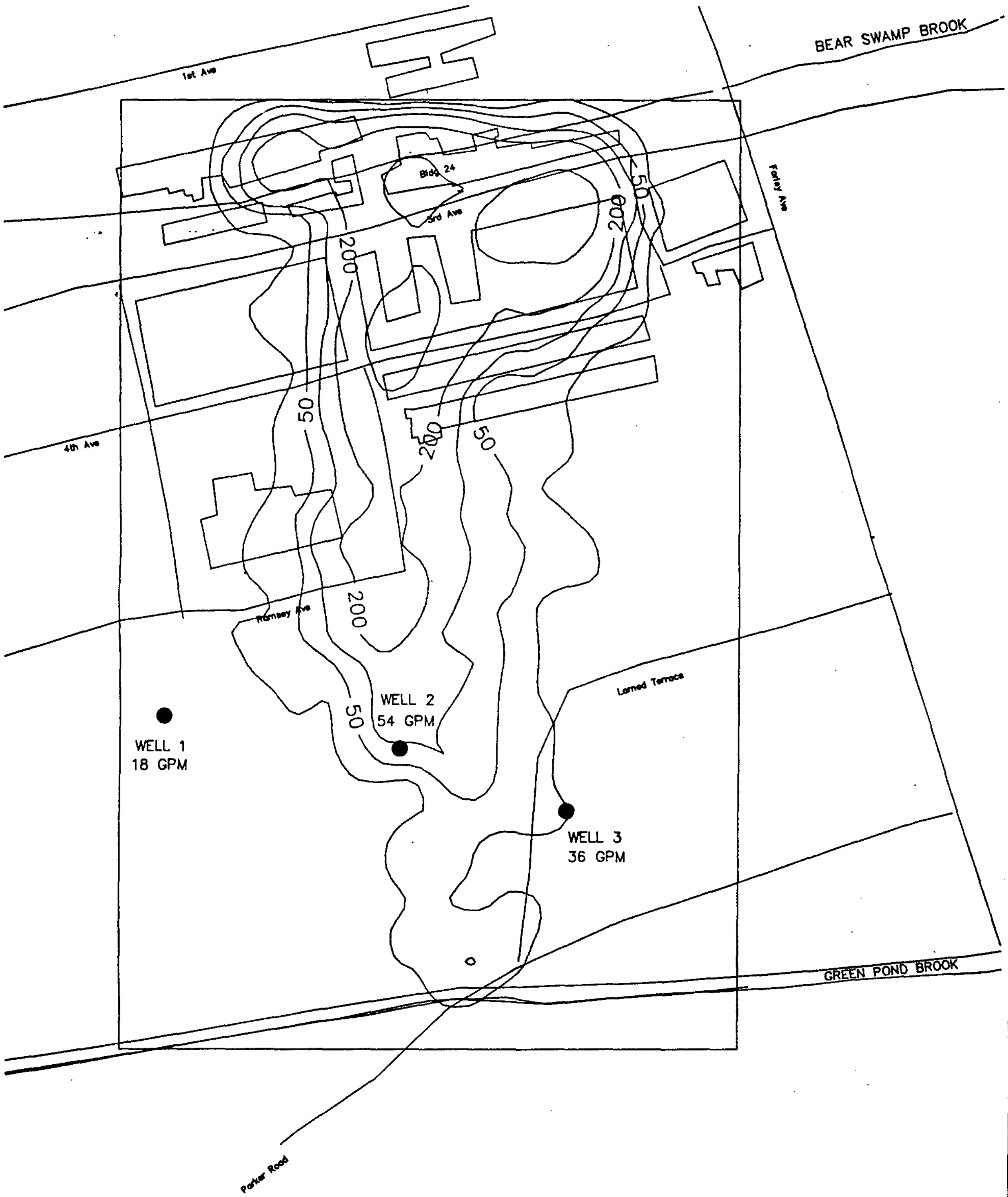

Figure III-51

DESIGNED DHK 3/89 DATE DRAWN PPM 3/89 DATE CHECKED ______ DATE APPROVED ______ DATE	ENGINEERING TECHNOLOGIES ASSOCIATES, INC. ENGINEERS • PLANNERS • SURVEYORS 3408 ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING SENSITIVITY ANALYSIS – CONTINUOUS SOURCE COLLECTION WELLS WITH VARIABLE PUMPING TCE CONCENTRATIONS (ppb) – YEAR 3 SCALE 1"=200' CONTRACT NO. 8313.10 DATE 3/27/89 SHEET

glacial aquifer. The diversion of pumpage from well 1 to well 2 lessens the vertical hydraulic gradient in the confining layer under well 1, which enables TCE to travel through the confined glacial aquifer and up through the confining layer under Green Pond Brook. TCE moving through the confined glacial aquifer under wells 2 and 3 is effectively captured by the wells.

Another unknown factor in the initial TCE distribution is the amount in the confining layer. The initial assumption was made that there was no TCE in the confining layer. This is probably not true. TCE that enters the water table aquifer at Building 24 would move both horizontally through the water table aquifer and vertically through the confining layer because of the downward flow gradient in this part of the valley. Another sensitivity analysis was performed to test the effectiveness of the proposed collection scheme on TCE that may be in the confining layer at the start of pumping.

TCE was distributed in the confining layer by running the RAND3D model for seventeen years with a continuous source at Building 24. The particles not in the confining layer were removed, and the model restarted using the steady state velocity vectors resulting from the original collector well scenario, three wells each pumping at 36 gpm at the proposed locations on the golf course. There were no additional sources of TCE in this model run. The model was run for four time steps of ten years each. At the end of that fourty year period, 50 percent of the initial TCE had been removed from the aquifer by the wells or by Green Pond Brook, 45 percent by the wells, and 5 percent by Green Pond Brook. The percentage collected by the wells declined with time as part of the TCE plume tended to move down the valley and away from the collector wells.

With no data on the amount currently present in the water table aquifer, it is not possible to predict the amount of contamination that could enter Green Pond Brook via traveling down through the confining layer, through the confined glacial aquifer, and up through the confining layer to the stream. Based on the above simulation, it may be estimated that approximately 80 to 90 percent of this contamination will be effectively collected by the proposed collector wells. If there is a significant quantity of TCE in the confining beds, the collector well system will have to be operated for many years. Continued monitoring of TCE concentrations in the confined glacial aquifer is necessary to determine when the cleanup is complete.

e. Hydraulic Conductivity

Hydraulic conductivity is one of the most important parameters in the model. Hydraulic conductivities are known

at some places due to pump test data. The model was calibrated at steady state, so hydraulic conductivity may be assumed to be approximately correct in the aggregate. The pump testing results indicate large variations in hydraulic conductivity from place to place in the water table aquifer, and the calibration was achieved using a single value of hydraulic conductivity in the water table aquifer, 20 ft/day. The impact of variations in hydraulic conductivity in the water table aquifer was tested for both the no action and collection wells with variable pumping scenarios.

A distribution of hydraulic conductivity in the water table aquifer was derived from the specific capacity and slug test data (see Table III-2). The data were distributed through the aquifer using the same algorithm that was used to create the initial head data files (see III.B.6. above). There was no significant trend in the data, so the average value of hydraulic conductivity, 20 ft/day, was used as a flat trend surface. The XDAT2 program was used to distribute hydraulic conductivity throughout the model grids using a nondirectional inverse distance squared weighting procedure. The result of this process is shown in Figure III-52. Hydraulic conductivity varies almost two orders of magnitude across the model grid.

The MODFLOW model was run at steady state with the heterogeneous hydraulic conductivity. All other inputs were as previously described. The steady state water table elevations are shown in Figure III-53. The results are reasonably close to the original calibration. Table III-4 shows the comparison of the model results with distributed hydraulic conductivity to the observations well data. The average error is -0.89 feet, and the root-mean square error is 3.01 feet. These results are not as good as the calibration, but indicate that this sensitivity analysis is not an unbelievable situation.

The no action scenario was rerun with the steady state heads based on the heterogeneous water table aquifer. Figure III-54 shows the removal of TCE from the aquifers by Green Pond Brook. After two years, 32 percent of the TCE has entered the stream. After ten years, 97 percent has entered the stream. There is a high hydraulic conductivity zone on the east side of the model. This zone becomes a preferential pathway for TCE to rapidly travel to Green Pond Brook. Figure III-55 shows the TCE concentrations in the water table aquifer after four years. The plume has shifted slightly to the east reflecting the large hydraulic conductivity in this area. The peak TCE concentration in seepage, averaged over the simulated stream reach, reaching Green Pond Brook is 112 ppb.

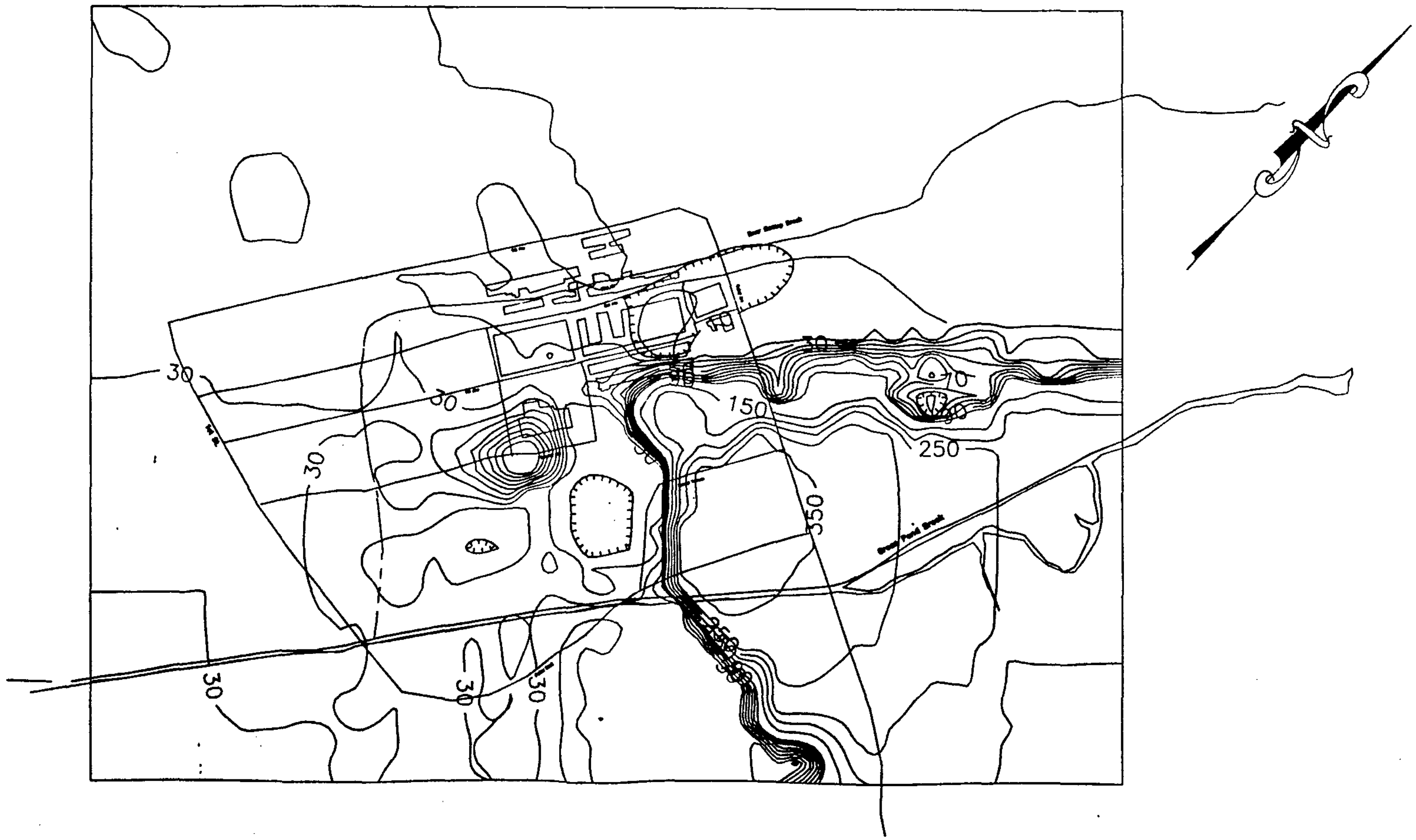

Figure III-52
WATER TABLE AQUIFER

REVISIONS	ENGINEERING TECHNOLOGIES ASSOCIATES, INC. ENGINEERS • PLANNERS • SURVEYORS	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING SENSITIVITY ANALYSIS – WATER TABLE DISTRIBUTED HYDRAULIC CONDUCTIVITY HYDRAULIC CONDUCTIVITY CONTOURS 8313.10 3-23-89

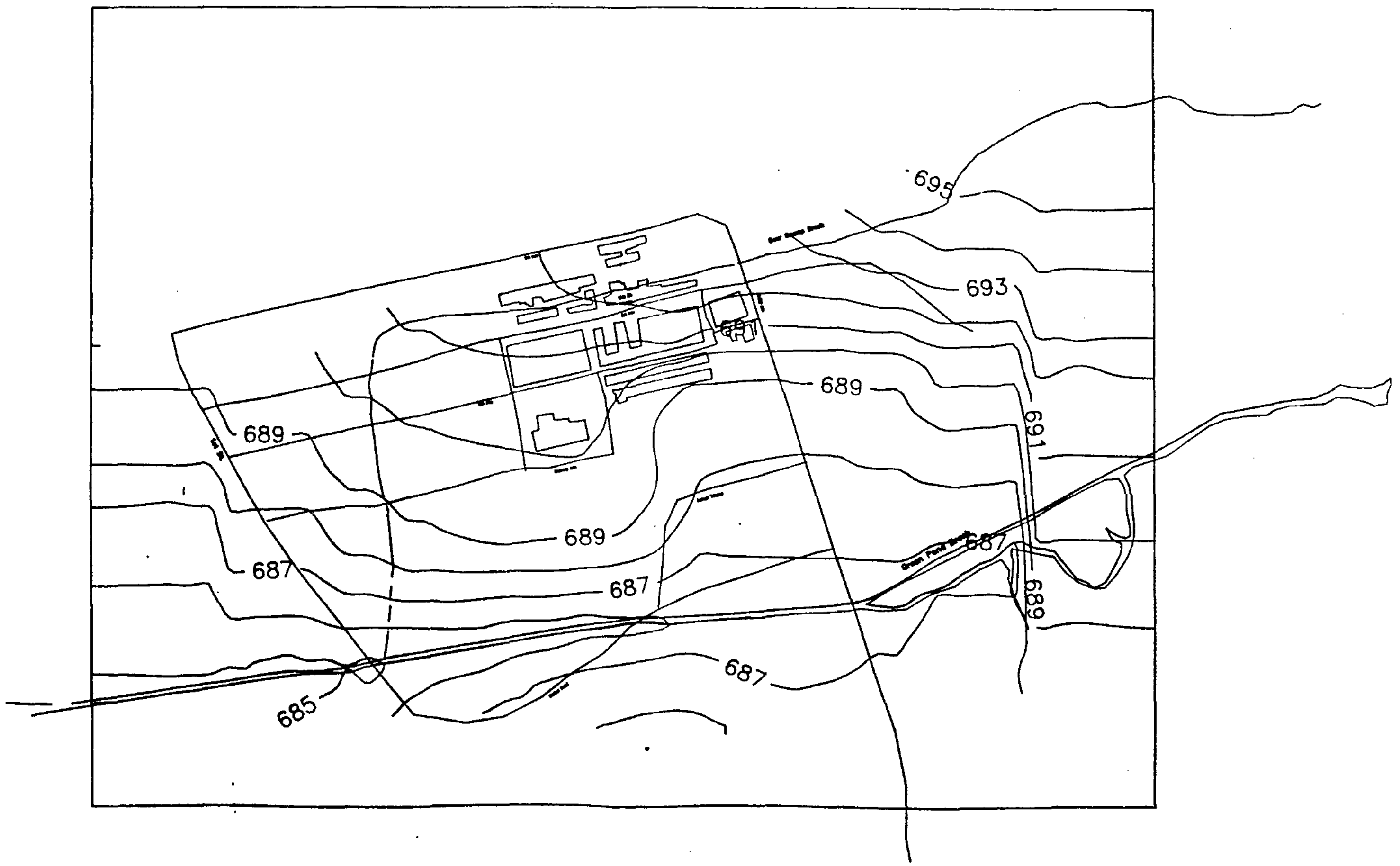

Figure III-53

WATER TABLE AQUIFER

REVISIONS	ENGINEERING TECHNOLOGIES ASSOCIATES, INC. ENGINEERS • PLANNERS • SURVEYORS	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING SENSITIVITY ANALYSIS - WATER TABLE DISTRIBUTED HYDRAULIC CONDUCTIVITY STEADY STATE HEAD ELEVATIONS 8313.10 3-23-88

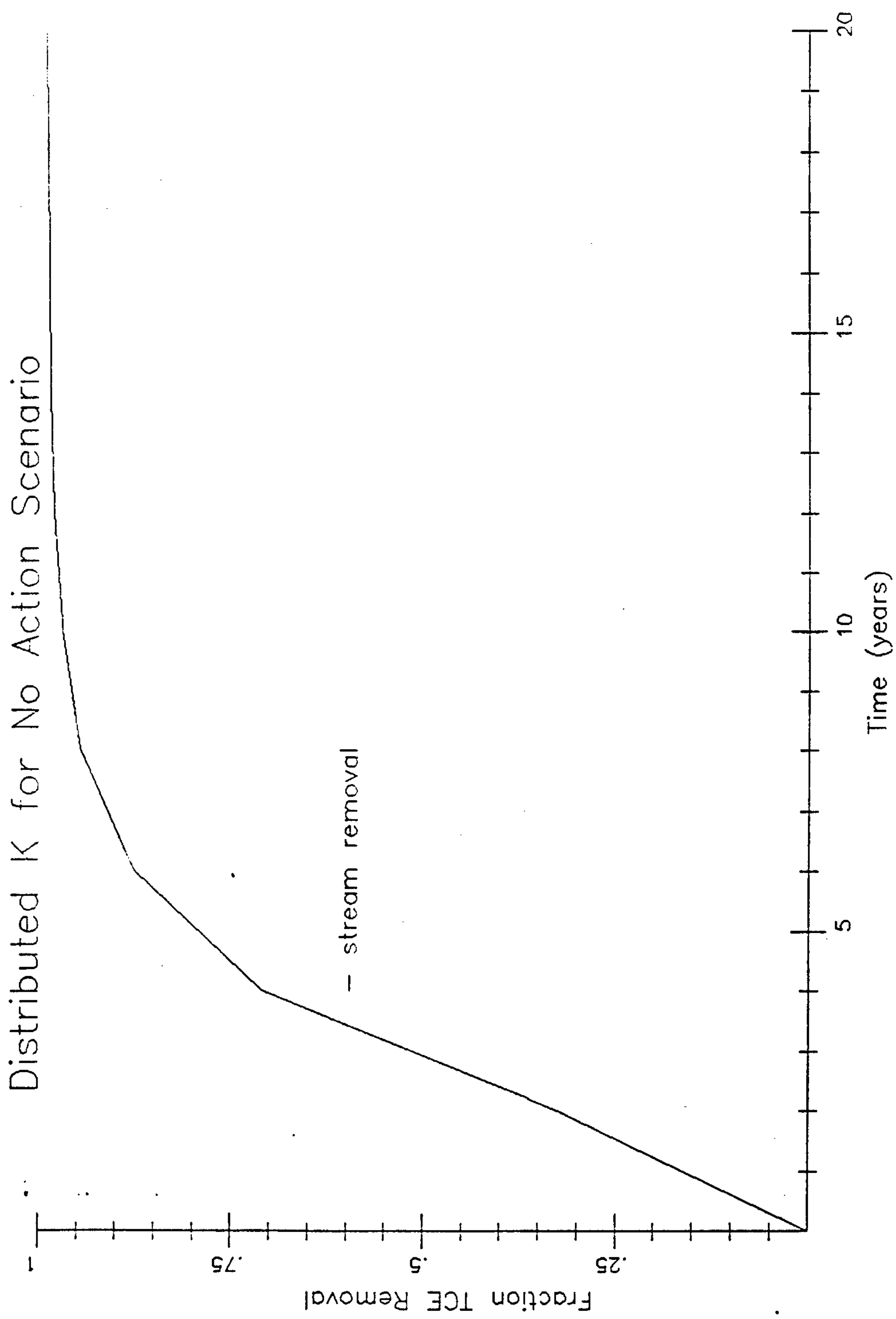

Figure III-54

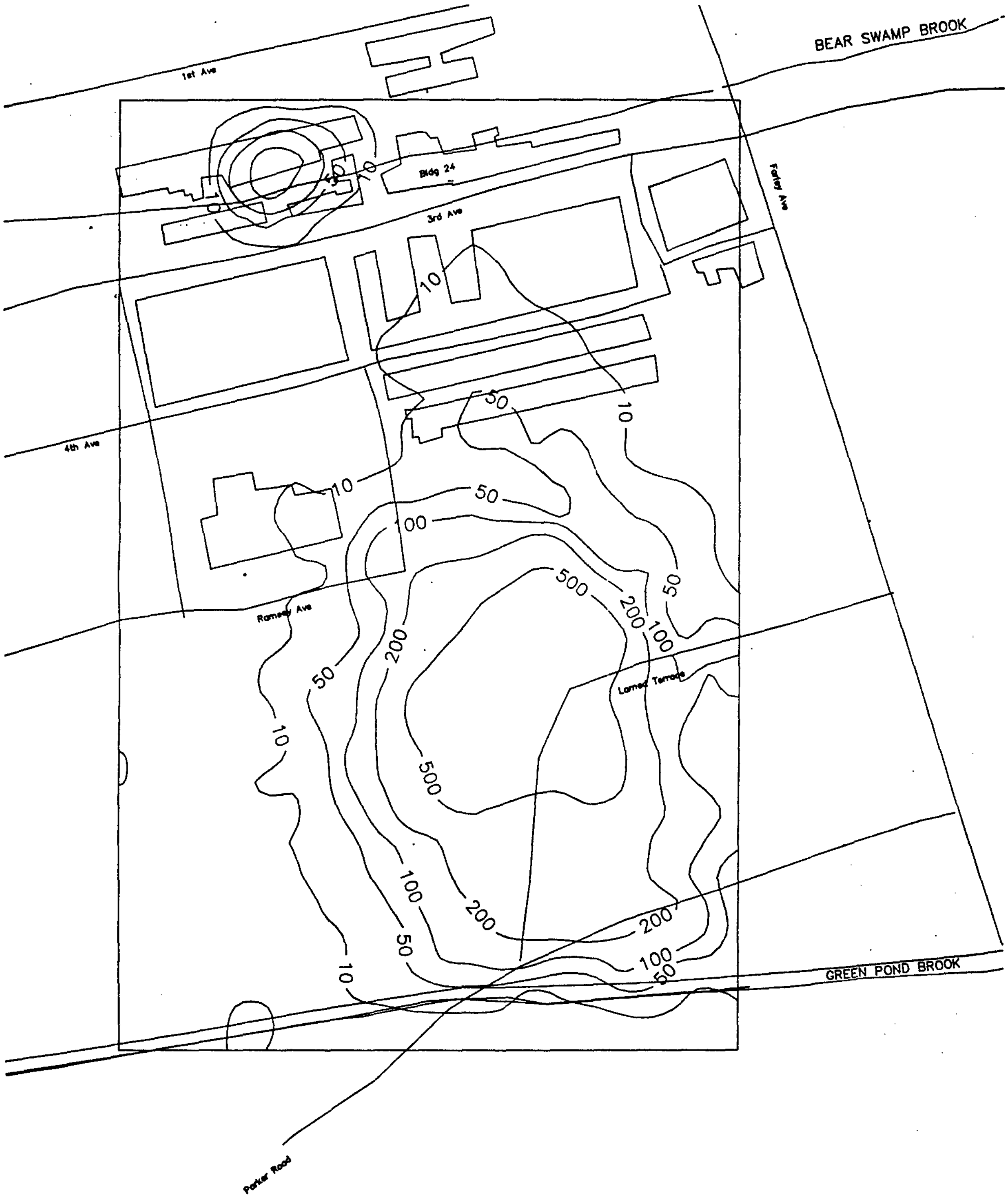

Figure III-55

WATER TABLE AQUIFER

DESIGNED DHK 3/89		ENGINEERING TECHNOLOGIES ASSOCIATES, INC.	PICATINNY ARSENAL, N.J. GROUNDWATER MODELING
DRAWN PPM 3/89		ENGINEERS • PLANNERS • SURVEYORS	SENSITIVITY ANALYSIS – DISTRIBUTED 'k' NO ACTION SCENARIO TCE CONCENTRATION (ppb) – YEAR 4
CHECKED		3400 ELLICOTT CENTER DRIVE SUITE 101 ELLICOTT CITY, MARYLAND 21043	SCALE 1"=200' CONTRACT NO. 8313.10 DATE 3/27/89 SHEET
APPROVED			

Table III-4
Comparison of Steady State Model with Heterogeneous Hydraulic Conductivity in Water Table Aquifer with Observation Well Data

7	30	1	689.54	689.07	-.47	I-2
7	31	1	687.80	688.71	.91	I
8	17	1	690.55	690.56	.01	65-4
9	38	1	685.32	685.23	-.09	41-4,5
10	39	1	685.96	685.91	-.05	41-3
11	24	1	689.30	689.93	.63	H-4
13	11	1	692.30	691.64	-.66	64-1
13	29	1	688.83	689.19	.36	112-9,10
15	12	1	693.69	691.37	-2.32	9-D
17	11	1	693.56	691.61	-1.95	9-E
17	12	1	692.00	691.32	-.68	31-1
17	28	1	689.12	689.37	.25	112-6,7,
17	38	1	688.30	686.10	-2.20	41-1,2
18	8	1	696.10	692.31	-3.79	9-C
18	10	1	693.10	691.89	-1.21	9-B
18	16	1	691.80	690.21	-1.59	CAF-2
18	17	1	691.72	690.01	-1.71	CAF-6
18	23	1	690.40	689.66	-.74	92-3,4,5
18	36	1	686.90	686.14	-.76	41-8,9
19	11	1	692.30	691.60	-.70	31-3A
20	9	1	693.00	692.22	-.78	9-A
21	6	1	696.36	692.55	-3.81	10-3
21	18	1	690.60	689.13	-1.47	130-3
21	28	1	689.39	688.65	-.74	112-3,4,
23	12	1	692.37	691.36	-1.01	31-2A
23	16	1	690.60	689.24	-1.36	34-1
24	19	1	691.20	688.75	-2.45	111-1,2
25	12	1	694.57	690.91	-3.66	31-5
25	15	1	693.41	689.52	-3.89	34-2
26	8	1	693.50	692.46	-1.04	24-1
26	15	1	692.32	689.45	-2.87	CAF-5
27	29	1	689.61	687.31	-2.30	112-1,2
29	18	1	690.10	688.63	-1.47	129-OBS
8	17	2	695.80	690.45	-5.35	65-3
11	24	2	689.54	689.92	.38	H-3
19	16	2	689.80	690.85	1.05	CAF-4,3
2	40	3	673.25	686.83	13.58	39-1
8	17	3	688.20	690.55	2.35	65-1,2
11	24	3	687.70	690.04	2.34	H-2
19	17	3	696.40	690.85	-5.55	CAF-1
21	6	3	697.90	696.19	-1.71	10-3A

LAYER	WELLS	AVG DIFFERENCE	RMS
1	33	-1.32	1.84
2	3	-1.30	3.15
3	5	2.20	6.77
TOTAL	41	-.89	3.01

The collection wells with variable pumping scenario was run with the heterogeneous hydraulic conductivity. The initial heads for this model run were the steady state heads derived for this distribution of hydraulic conductivity. The proposed distribution of pumping rates between the three wells was infeasible; wells ran dry at the proposed pumping rates. Well 2 was in a low permeability zone, 5.7 ft/day. Well 3 was in a node with a hydraulic conductivity of 11 ft/day. Well 1 was in a node with a hydraulic conductivity of 53.4 ft/day. It was necessary to rearrange the pumping rates in the scenario as follows:

Well	Column	Row	Pumping Rate (ft^3/day)
1	9	27	6930
2	17	28	3465
3	23	30	11551 for 1st year
			11551 for 2nd year
			10396 beyond

All other inputs to the model were as described above for the collection well with variable pumping scenario. Steady state was reached at about three years. Figure III-56 shows the steady state water table with the continuous pumping for the third year and beyond. Steady state well drawdowns are shown below.

Well	Drawdown (ft)
1	3.2
2	8.3
3	8.4

Figure III-57 shows the removal of TCE from the aquifers over time with the collection wells with variable pumping scenario. After three years, 74 percent of the TCE has been removed from the aquifers with 69 percent removed by the collector wells and five percent entering Green Pond Brook. After six years, 95 percent has been removed from the aquifers with 89 percent removed by the wells and six percent by the stream. Figure III-58 shows TCE concentrations in the water table aquifer after three years. The peak concentration of TCE in seepage to Green Pond Brook (averaged over the simulated reach) is 33 ppb.

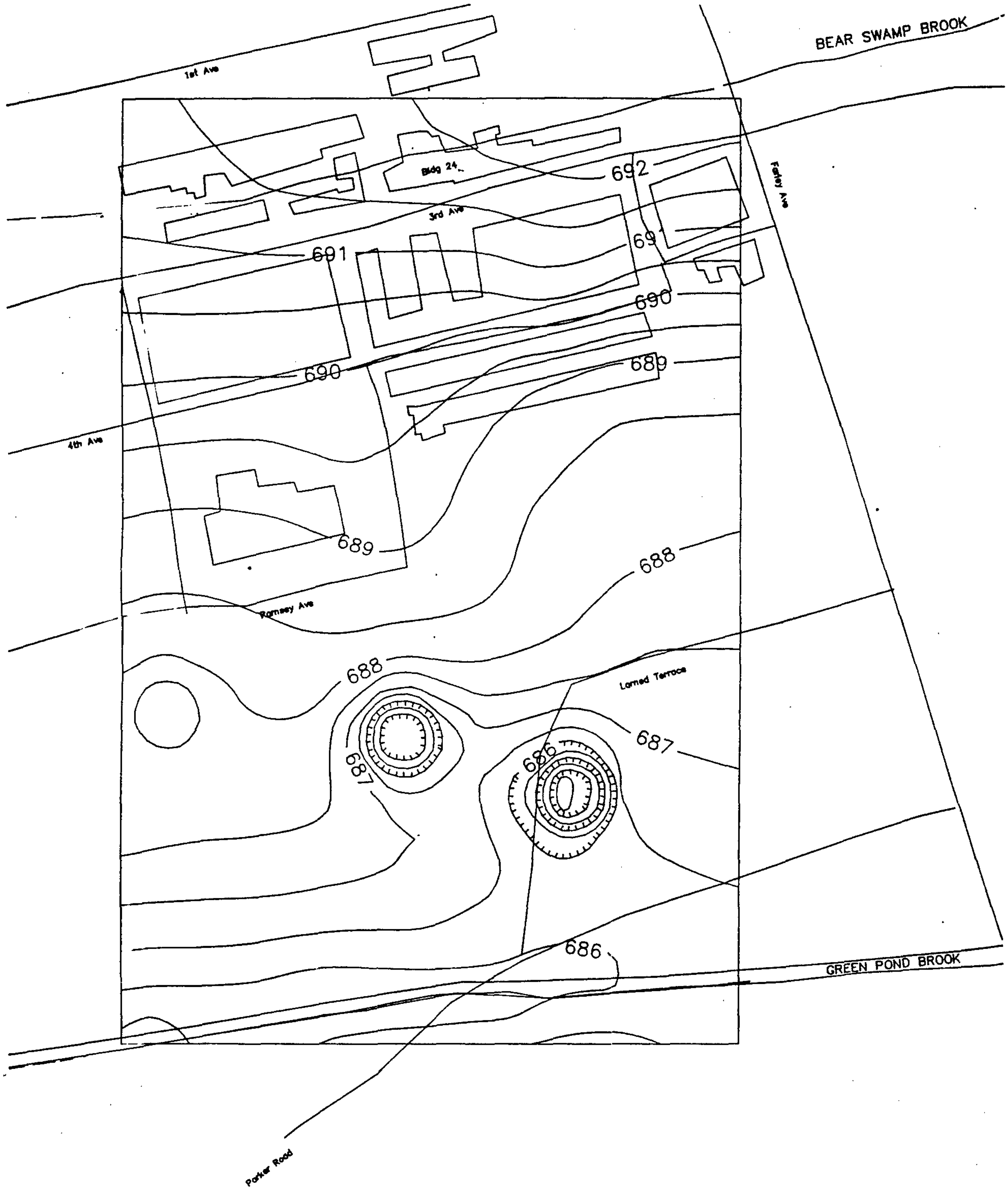

Figure III-56

WATER TABLE AQUIFER

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DRAWN PPM 3/89	
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ELLICOTT CITY, MARYLAND 21043

PICATINNY ARSENAL, N.J. GROUNDWATER MODELING
SENSITIVITY ANALYSIS–DISTRIBUTED 'k'
COLLECTION WELLS WITH VARIABLE PUMPING
STEADY STATE WATER TABLE

SCALE 1"=200' | CONTRACT NO. 8313.10 | DATE 4/12/89 | SHEET

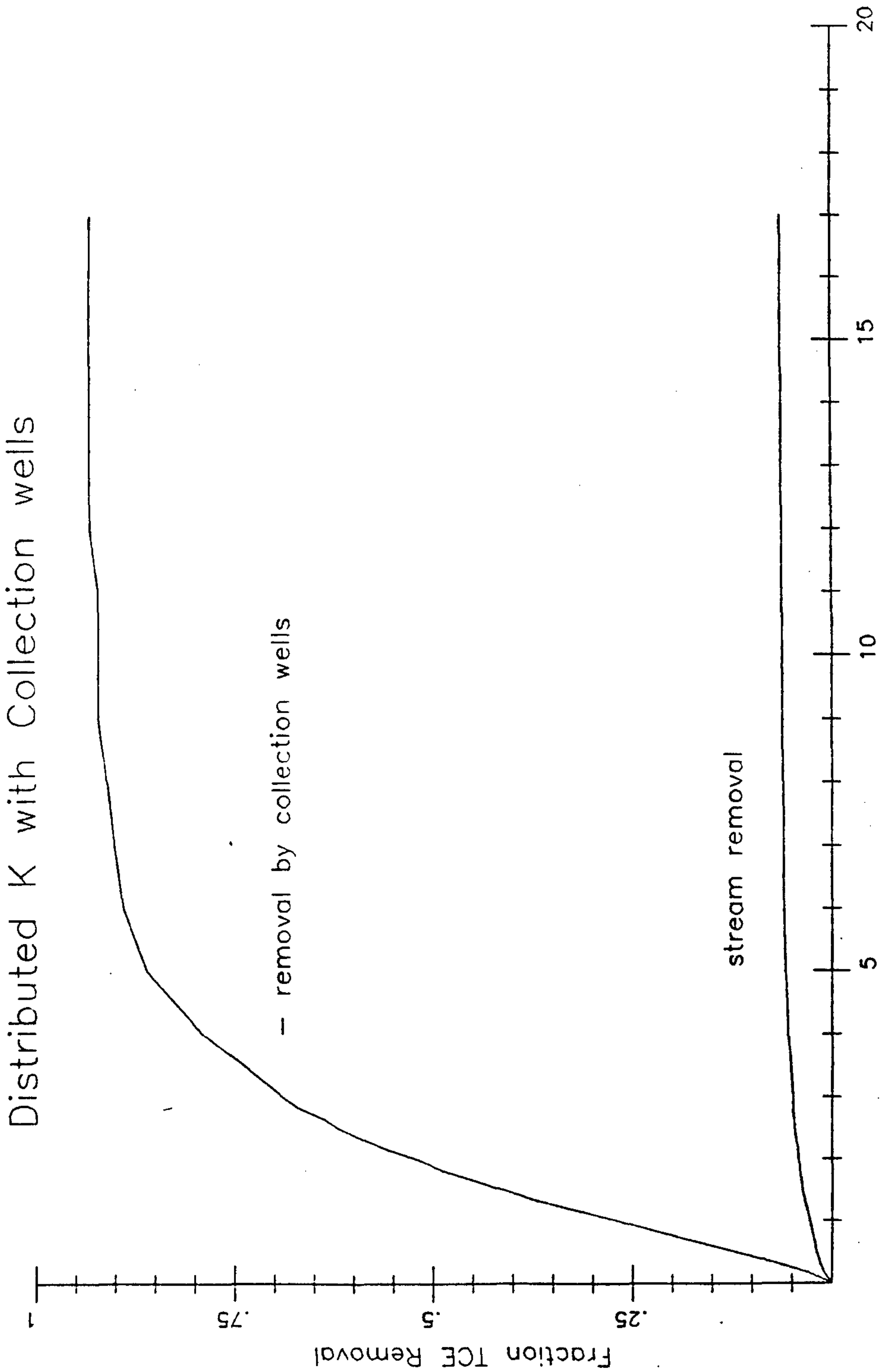

Figure III-57

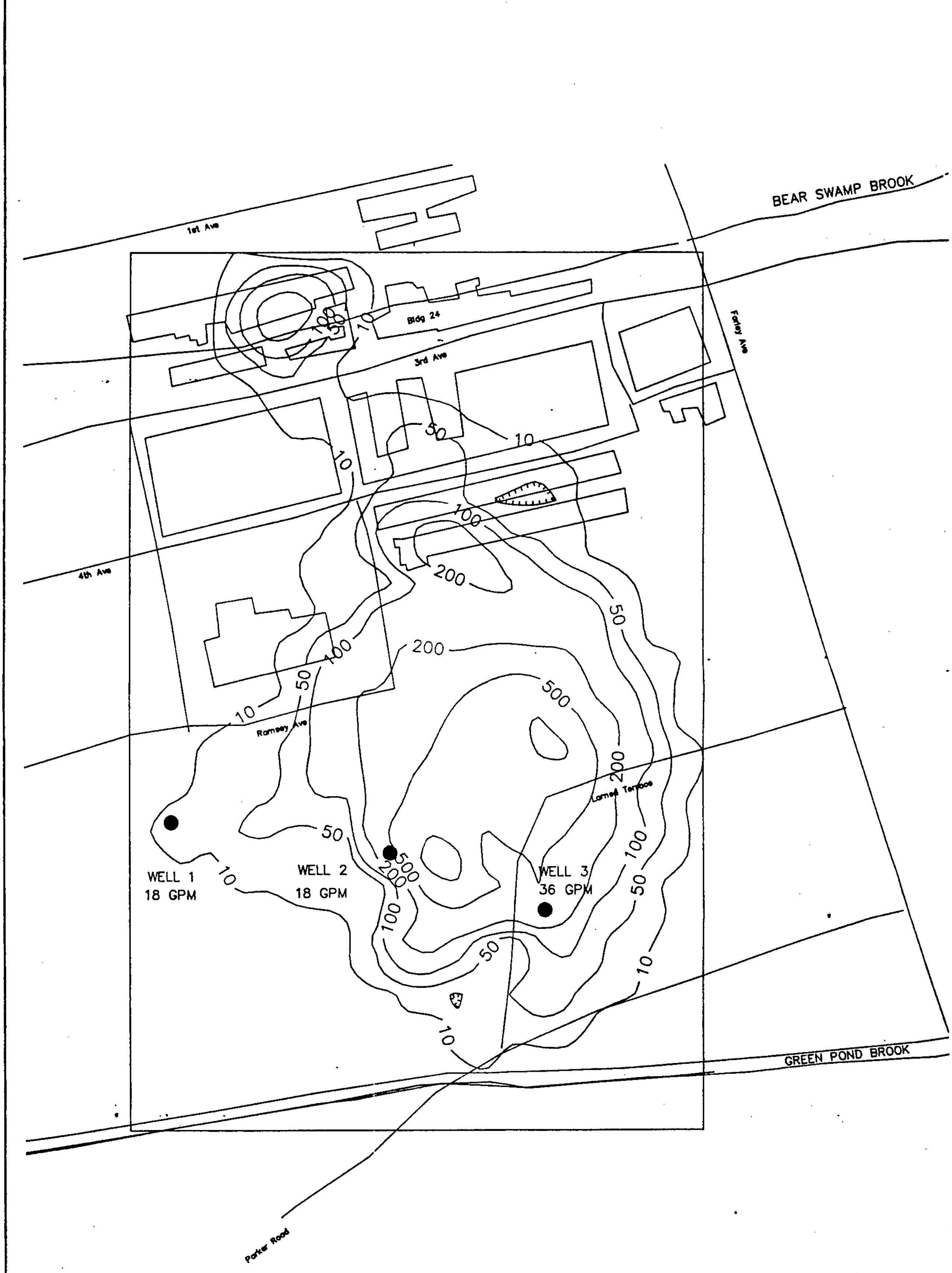

Figure III-58

WATER TABLE AQUIFER

DESIGNED	DHK	3/89	
DRAWN	PPM	3/89	
CHECKED			
APPROVED			

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3400 ELLICOTT CENTER DRIVE SUITE 101
ELLICOTT CITY, MARYLAND 21043

PICATINNY ARSENAL, N.J. GROUNDWATER MODELING

SENSITIVITY ANALYSIS – DISTRIBUTED 'k'
COLLECTION WELLS WITH VARIABLE PUMPING
TCE CONCENTRATIONS (ppb) – YEAR 3

SCALE 1"=200' | CONTRACT NO: 8313.10 | DATE 3/27/89 | SHEET:

IV. Conclusions and Recommendations

The conclusions and recommendations of this study are presented in two sections. The first section summarizes the results of the remedial action plan design simulations and makes recommendations for a collector well system at the Building 24 site. The second section states some conclusions and makes some recommendations for the further development of the models used in this study.

Recommended Pumping Scheme for Remedial Action

The results of the modeling of the Building 24 TCE plume at the Picatinny Arsenal indicate that there is no clearly superior pumping design for cleaning up the contaminated ground water and preventing TCE from reaching Green Pond Brook. All of the scenarios simulated, that do not include recharge wells upgradient of Building 24, achieve similar long term removal rates. Recharge wells would speed the removal of TCE from the aquifer, but effective recharge wells may not be feasible because of a shallow water table and the likelihood of injection well clogging. The pumping plans that remove ground water from the aquifer rapidly collect more TCE from the water table aquifer faster. All the collection well scenarios simulated are effective in forming a barrier to the movement of TCE towards Green Pond Brook. Placing collector wells closer to Green Pond Brook, would effectively collect more of the TCE and lower the amount entering Green Pond Brook, but result in larger amounts of pumpage containing lower concentrations of TCE.

The recommended collector well layout is three wells spaced at approximately 480 feet that span the plume of contamination from Building 24. These wells may be placed in the rough of the golf course. The locations are recommended in the body of the report.

All of the scenarios tested will remove TCE from the water table aquifer effectively. TCE concentrations in the collector wells should be less than 5 ppb after less than 10 years of continuous pumping. After six years of pumping, between 91 and 95 percent of the TCE will have been removed from the aquifers by any of the collection well plans simulated.

All of the scenarios tested will form a flow barrier in the water table aquifer. They are also all relatively effective in forming a flow barrier in the confined glacial aquifer. Pumping schemes that pump less ground water from the most down valley proposed collection well for reasons of efficiency are slightly less effective in collecting TCE from the confined glacial aquifer than schemes that pump

equal amounts from each well. The flow direction in the confined glacial aquifer has a larger down valley component than in the water table aquifer, so contamination in the confined glacial aquifer travels down valley.

The amount of TCE which enters Green Pond Brook is negligible under any scenario, including the no action scenario. The maximum instream concentration of TCE in Green Pond Brook would be approximately 5 ppb under the no action scenario. The various collection well plans may reduce this concentration to about 2 or 3 ppb. After collection well pumping has been established (approximately six months), negligible amounts of TCE reach the stream. The peak TCE concentration in stream seepage occurs prior to stabilization occurring.

The treatment system for the contaminated pumpage should be designed conservatively. The maximum pumpage rate will be approximately 150 gpm. The peak composite concentration of TCE in the pumpage from three collector wells would be approximately 750 ppb.

Sensitivity analysis indicates that the results of the analysis are robust. If adsorption is an important factor, the proposed pumping schemes will still be effective, but the cleanup will take longer, possibly as long as twenty years for the same fraction of TCE removal from the aquifers as was achieved in six years with the base assumptions. Dispersivity has relatively little impact on the proposed remedial actions. If there is still a source of TCE at or near Building 24, the proposed remedial actions will effectively control it. If hydraulic conductivity is different than assumed, some changes in the proposed pumping rates may be necessary, but an effective pumping plan may still be implemented. The simulations have made relatively conservative assumptions for the other uncertainties in model parameters.

There are several important considerations in actually designing and installing the proposed collection wells. Three wells are recommended at the approximate locations detailed in the report. The wells should be drilled with a minimum diameter of 12 inches and cased with 6 inch casing. The wells should be logged carefully during drilling. The completion interval of the wells should be in the bottom one-third of the saturated thickness. The screened interval should be restricted to sand and gravel zones. Multiple completion intervals should be considered if clay lenses are encountered in the drilling. It is important that these wells be designed to obtain the maximum yield obtainable, so as to collect the maximum amount of contamination. Samples of the completion zone should be collected and analyzed for the sizing of gravel pack and screen slots. Top quality stainless steel screen with the maximum possible open area

should be selected. If the first well drilled at a selected location is a low yielding well in clay strata, consideration should be given to moving twenty feet and drilling a new well. All collector wells should be adequately developed by appropriate means.

After pumps are installed in the wells, pump tests should be performed on each of the collection wells. First, a step test should be performed with a minimum of three different pumping rates at a duration of two hours each. After water levels have recovered in the well, a long (>24 hour) constant rate pump test with water level monitoring at observation wells should be performed. The results from these tests will indicate what pumping rates may be maintained by the wells under long term conditions. At this point, the model developed as part of this study could be used to refine the collection well pumping rate schedule.

The pumping rates for the collector well may have to be adjusted based on actual field experience. Rates should be adjusted so that each collection well causes a substantial depression in the water table. Wells should not be pumped dry, however, pumping rates should be adjusted based on operating experience and monitoring results. The total period of pumping will depend on how quickly TCE contamination may be drawn to the collection wells. When pumpage contains less than detectable levels of TCE for six months to one year, the water table aquifer would be clean.

The treatment system may be placed at any convenient place. If it is placed close to Building 24, discharge of the treated water to Bear Swamp Brook may increase recharge and thus speed the aquifer cleanup, although model simulations indicate that this effect may be marginal.

Modeling

The United States Geological Survey three dimensional, finite difference ground water model (MODFLOW) was successfully applied and calibrated at steady state to the Building 24 site at the Picatinny Arsenal. A three layer simulation was performed of the glacial aquifers and shallow bedrock at the site. The model was calibrated to observation well water levels from the fall of 1987. The available data on aquifer characteristics was utilized. The results of the flow modeling generally match the interpretations from previous studies.

A new program was written to translate the output of the MODFLOW model to a format suitable for input to the three dimensional, random-walk solute transport model (RAND3D). This program (PREMOD3D) computes three dimensional velocity vectors and sink (wells, gaining streams) locations for input to RAND3D.

A new interactive, graphic version of the RAND3D model was prepared for this project. Numerous improvements were made to the model. The model was written in a general form so it may be easily applied to other projects.

In the development and use of the PREMOD3D and RAND3D models, areas of possible improvement were noted. Since the primary objective of this project was the design of a ground water control plan for the Building 24 ground water contamination plume at the Picatinny Arsenal, the models were only written to include the necessary features. The model routines were written, however, in a general style so that the models could be applied to other sites. Recommendations for improvements to the models follow.

- More testing of both PREMOD3D and RAND3D is necessary. Both models should be able to accommodate almost any hydrogeologic problem that can be simulated by MODFLOW. Minor code modifications (redimensioning of arrays) and further testing should be conducted.

- RAND3D could be modified to run an enhanced graphics adapter and color monitor. This modification would permit greater use of color in the graphic displays, thus improving understanding of the model.

- More user friendly features could be added to RAND3D such as better error recovery and input data checking.

- Research on the optimum interpolation algorithm for three dimensional velocity interpolation should be performed. Testing of different algorithms with different types of problems would yield information of the trade-off between cost and accuracy.

- RAND3D could be rewritten in a different language. Possible candidates would be Microsoft QuickBasic 4.5 (the current QuickBasic), or Fortran, which would give portability to all computers, but lose the graphic interface.

- PREMOD3D and RAND3D could be modified to preserve the row and layer numbering scheme of MODFLOW for easier understanding.

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